THE RELATIONSHIP OF RUNOFF, FLOW-DURATION, AND NATURAL GROUND-WATER RECHARGE TO THE BASIN CHARACTERISTICS OF THE MAUMEE RIVER BASIN IN OHIO, INDIANA, AND MICHIGAN

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INTRODUCTION

PURPOSE

This report deals with the streamflow parameters of runoff, flow-duration, and natural recharge and their relation to specific basin characteristics. Daily stream discharges from 12 gaging stations were used to generate these parameters for the Maumee River Basin. In order to increase the accuracy of the results and take into account yearly fluctuations in streamflow, three years were choosen representing below normal, normal, and above normal discharges.

FORTRAN programs were used to compile hydrographs, flow-duration curves, and flow-duration data for each gaging station for each year. From these 72 computer print-outs, streamflow parameters were determined and then related to the geology, topography, land use, surficial deposits, and the hydrology of the sub-basins above the respective gaging stations. Studies of this type, depending on the basin, could be useful for purposes of agriculture, hydraulic engineering, development of water supplies, and flood control, among others.

LOCATION OF STUDY

The Maumee River Basin (Figure 1) drains approximately 6,586 square miles, 4,856 of which are in Ohio, 1,260 in Indiana, and 470 in Michigan. The St. Joseph River originates in Hillsdale County, Michigan and flows southwest through Ohio into Indiana. The St. Marys River, origination in Shelby County, Ohio, flows northwest into Indiana. At Fort Wayne these two rivers join to

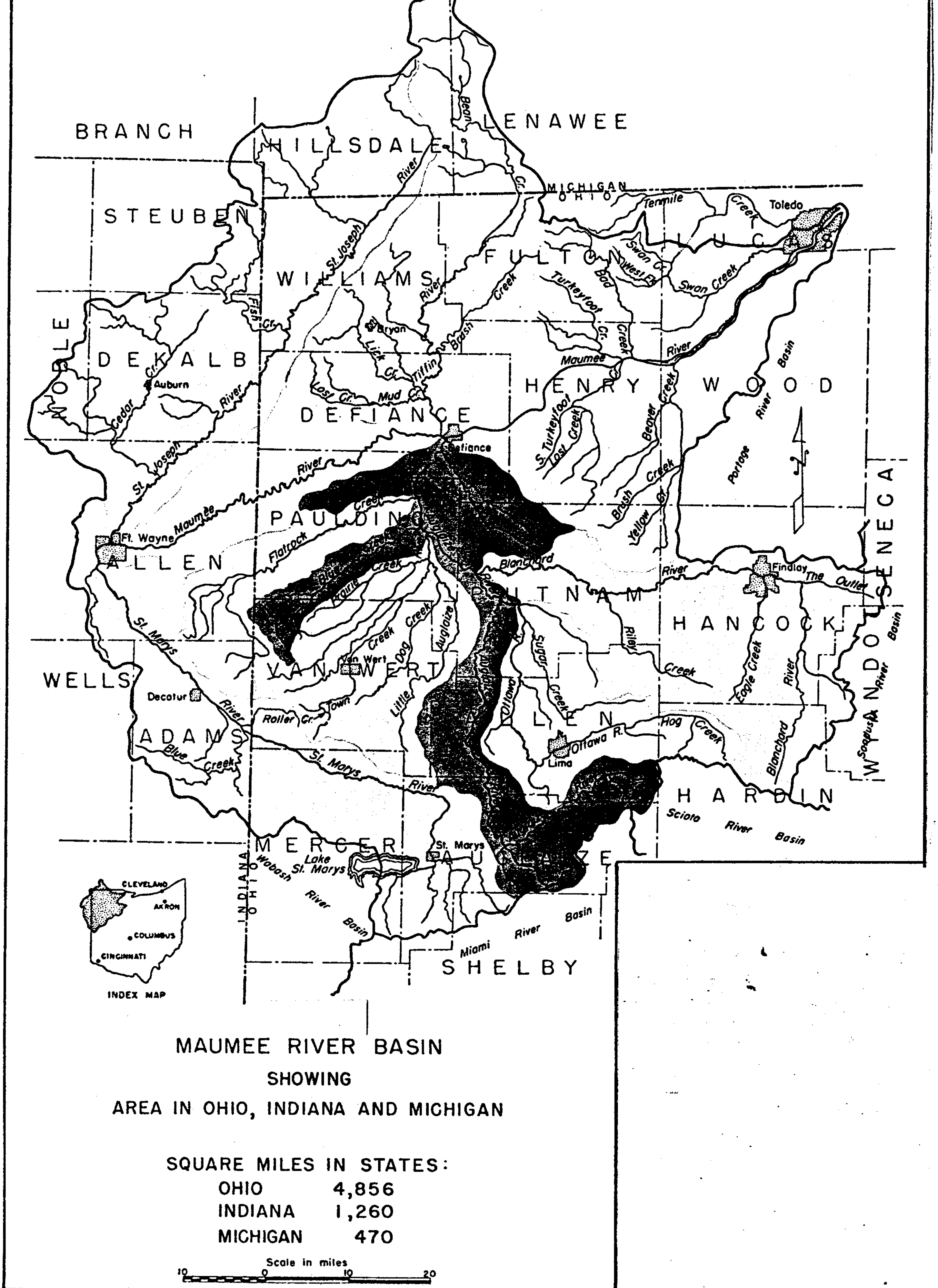

Figure 1. Location and Extent of Study Basins in the Maumee River Basin (from Ohio Department of Natural Resources, Division of Water, Report No. 11)

form the Maumee River which flows northeast through Defiance and into Lake Erie at Toledo. At Defiance the Tiffin River flowing south from Michigan and the Auglaize River flowing north from parts of Indiana and Ohio join the Maumee River. The tributaries of the Auglaize and Ottawa Rivers drain much of the lower portion of the Maumee Watershed (2300+ square miles).

PREVIOUS WORK

The various aspects of the hydrologic budget, including runoff and recharge, have been discussed by many authors.

Meinzer and Stearns (1928) were among the first to consider the problem of separation of the ground-water component of streamflow from total runoff. Linsley, Kohler, and Paulhus, (1958) explored many methods for the separation of streamflow components from hydrographs. Cable's (1971) paper explored hydrograph separation methods and the relation of precipitation to ground-water runoff using base runoff as an index to ground-water potential.

Rasmussen and Anderson, (1959), and Schicht and Walton (1961), established a relationship between ground-water levels in an aquifer and ground-water discharge to a stream. Both used hydrologic budgets for their estimates of ground-water discharge. Walton (1965) described many methods to calculate recharge rate, but many are usable only where rates of ground-water pumpage are known.

Cross and Hedges (1959) made a comparison of flow characteristics of streams using flow-duration curves. They stated that the shape of the duration curve is an index of the natural storage within a basin, including ground-water storage, that is used by the stream. Walton (1970) makes use of the ratio $(D_{25}/D_{75})^{\frac{1}{2}}$ (Pettijohn, 1949) which is the slope of a grain-size frequency-distribution curve, and equates it to the ratio $(Q_{25}/Q_{75})^{\frac{1}{2}}$ which is the slope of a flow-duration curve. Q_{25} and Q_{75} represent streamflow equaled or exceeded 25% and 75% of the time.

In 1975, Jack Tuller made a study of the Scioto River Basin of Ohio and related runoff, flow-duration and natural recharge to the basin characteristics. Tuller and John McKeon developed the computer programs used for the preparation of hydrographs and flow-duration curves and data from daily stream discharges.

GENERAL BASIN CHARACTERISTICS

TOPOGRAPHY

The basin is roughly circular in shape and about 100 miles in diameter. Much of the basin lies in the Glacial Lake Plains subprovince, the bed of the basin being extremely flat and featureless with the exception of beach ridges which are narrow, shallow sand hills extending for miles generally in an east-west direction. These ridges formed at the shores of the several stages of ancient Lake Maumee (Figures 2 and 3).

North and south of the old lake plain are the Till Plains which are flat to gently rolling. The morainal belts of the southern part of the basin are of low relief, whereas those of southern Michigan are more hummocky.

Elevations are generally higher around the edge of the basin and renge from 1,100 feet above sea level in southern Michigan to 650 feet in the central region to 570 feet at the mouth of the Maumee River. This topography yields average slopes for rivers as follows: Maumee--1.3 ft./mi., St. Marys--2.8 ft./mi., St. Joseph--1.6 ft./mi., Tiffin--1.2 ft./mi., Auglaize--3.2 ft./mi., Little Auglaize 2.5 ft./mi., Blanchard 0.9 ft./mi., and ottawa 4.0 ft./mi. Since some headwater tributaries orginate in the Till Plains, they can have gradients of up to 10 ft./mi.

LAND USE

The Maumee River Basin ranks first in Ohio with respect to percentage of land devoted to farming. Of the 17 Ohio, 4 Indiana and 2 Michigan counties wholly or partially within

Figure 2. Physiographic Boundaries in Ohio (from Ohio Water Plan Inventory, Report No. 22.)

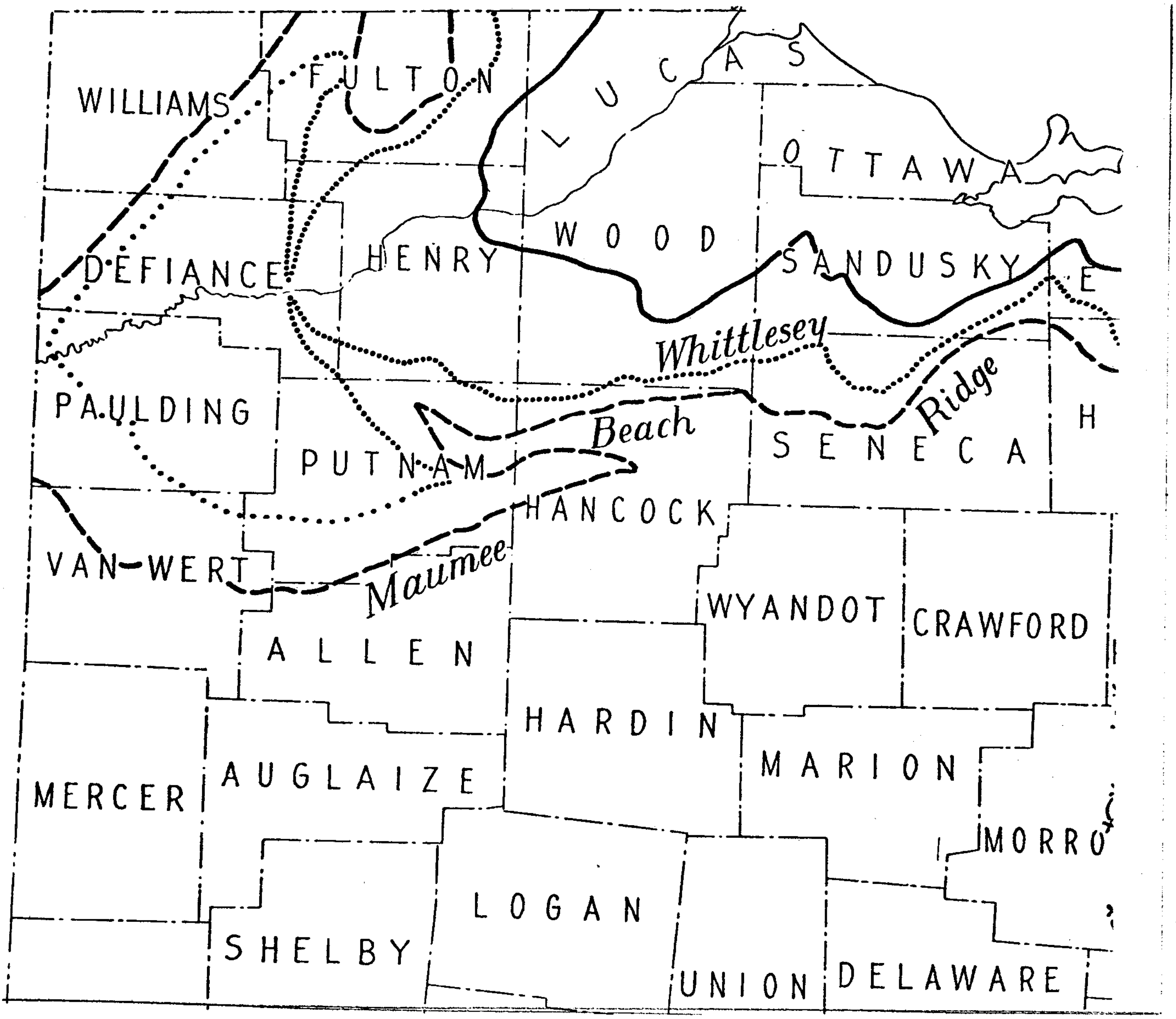

Figure 3. Ancient Beach Ridges in the Maumee River Basin (from Stout, W., et. al., 1943.)

the basin, only 3 have less than 90% of their land in agricultural use. These are Lucas and Allen counties in Ohio and Allen County in Indiana. Total area in farms has increased from approximately 40% in 1880-to 87.4% in 1954-to 92% in 1958-to approximatly 94% at present. The increase in cropland took place with a corresponding decrease in pasture and woodland. Lucas County and Wood County in Ohio and Allen County in Indiana have had a decrease in farmland due to the developement of suburbs near cities.

Only 6% of land use is represented by forest cover, most of which is confined to farm woodlots. However, woodland exceeds pasture land due to the predominance of grain farming and the abandonment of permant pasture in favor of rotation meadows.

Percentage of land in urban and other built-up development is highest in Lucas County, Ohio and Allen County, Indiana, both with approximately 45%. Almost half of the remaining counties have less than 5% of land use in this area.

Water storage has little effect on land use since the flat topography makes impoundment of water difficult. Approximately 10% of municipalities use up-ground reservoirs, the rest rely on ground-water.

CLIMATE

Climate is controlled by large flat areas to the west and southwest of the basin. A small area is influence by Lake Erie which moderates temperature in the spring and fall. Due to the basin's location, low pressure centers pass to the south of it and high pressure centers to the north. This accounts for prevailing winds from the south or southwest, making the basin less subject to severe storms, with less rainfall than the rest

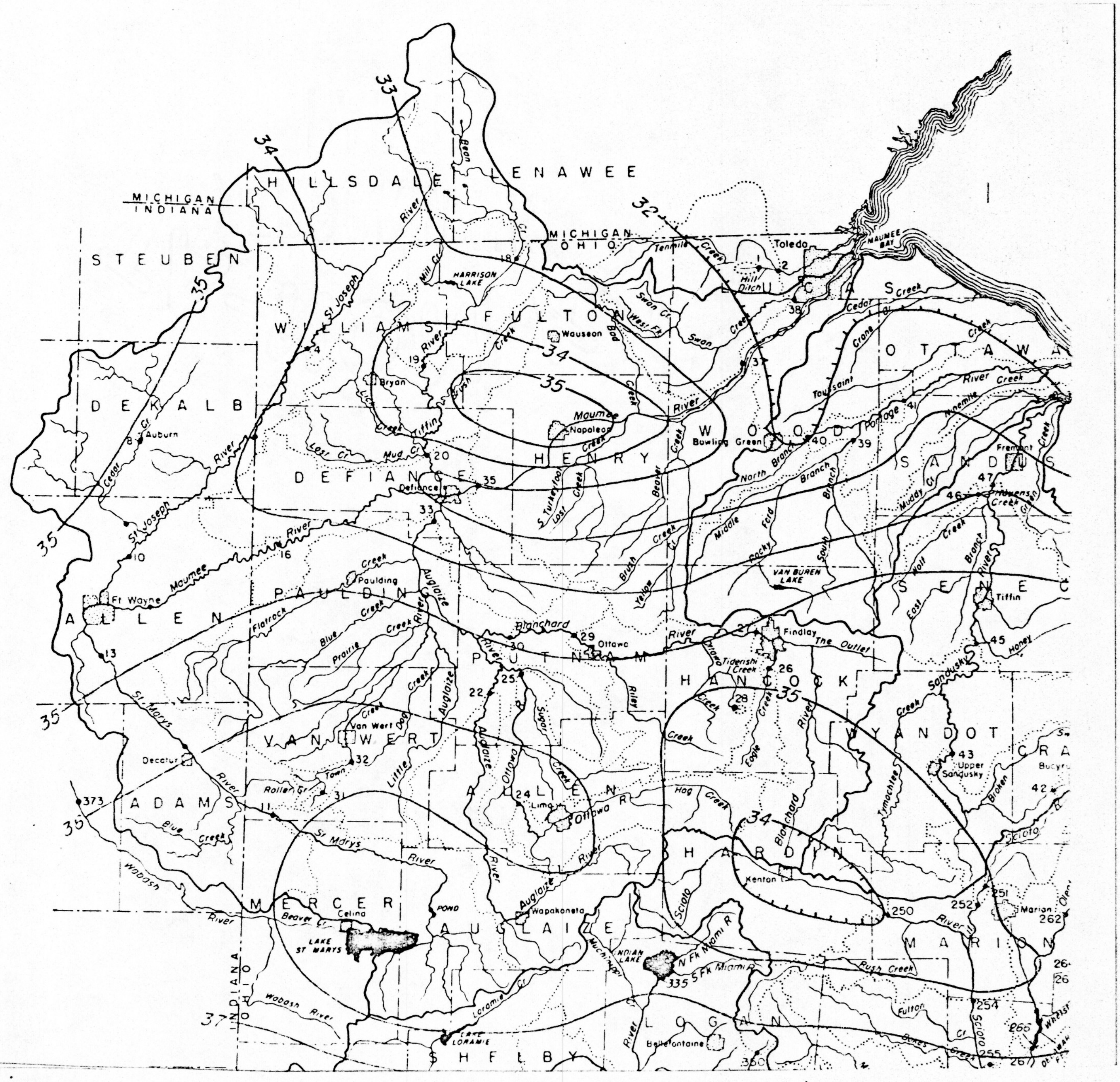

Figure 4. Mean Annual Precipitation (Invhes) in the Maumee River Basin (from Ohio Water Plan Inventory, Report No. 13, 1962.)

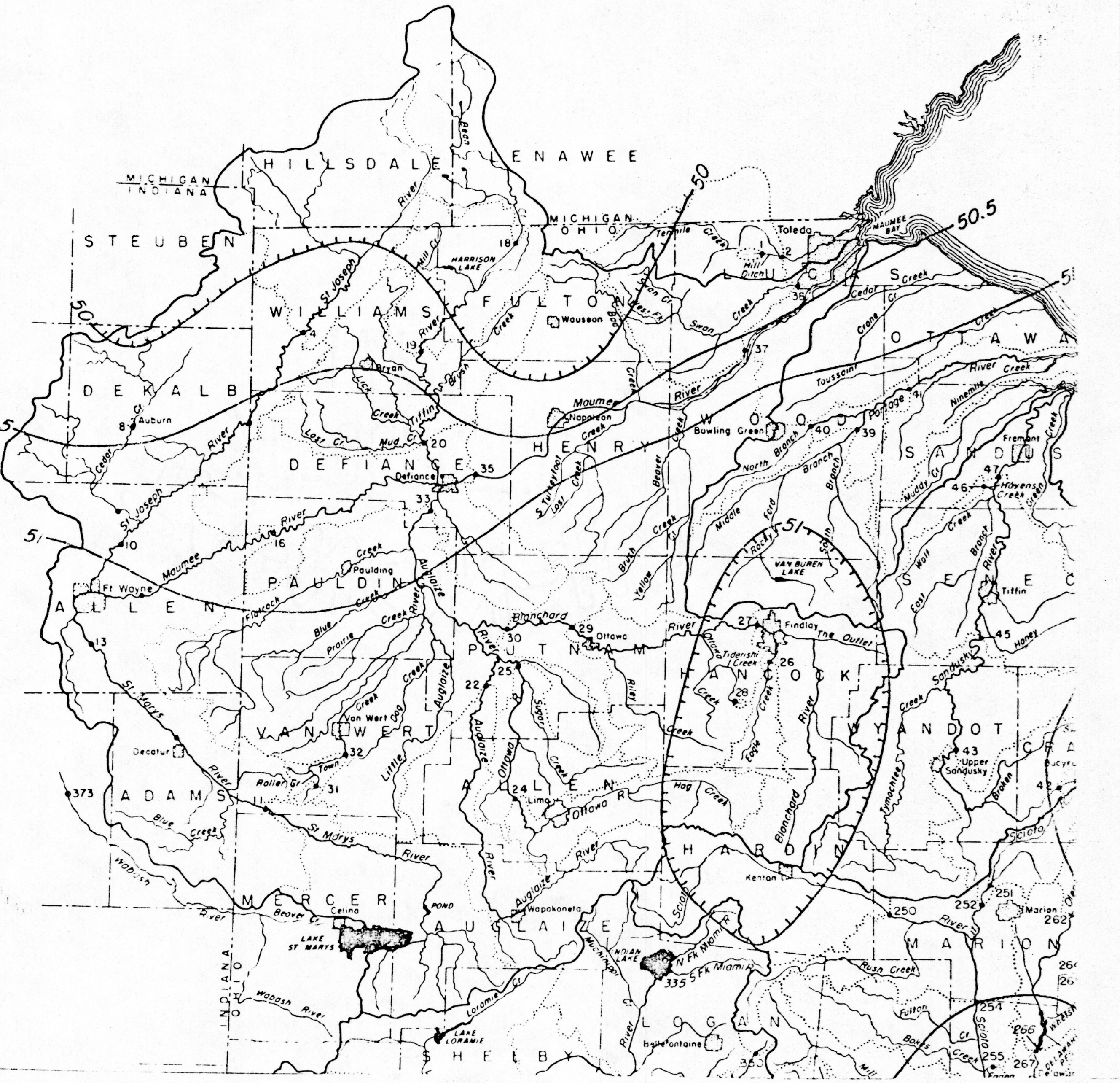

Figure 5. Mean Annual Temperature in the Maumee River Basin (from Ohio Water Plan Inventory, Report No. 13, 1962.)

of the state. Mean annual precipitation is 34 inches (Figure 4) and mean annual temperature for the basin is 50.6°F. (Figure 5).

BEDROCK GEOLOGY

The stratigraphic sequence of Silurian and Devonian formations are thick layers of limestone and dolomite, uniform in carbonate composition, but different in physical and hydrologic characteristics (Table I). Most of the sequence is dolomite, but due to the complex enviornment of deposition in Silurian and Devonian seas, variable hydrologic and chemical compositions of ground-water occur. There is a wide variety of structural and textural features, such as, coarse to fine bedding planes and cross-bedding. There is also direct precipitation from supersaturated water, chemical and biochemical deposits, massive barrier reefs and fragment deposition.

A major structural element of the area is the Cincinnati Arch, located in the east-central portion of the area. Major faults occur on the western flank of this anticline. The north-trending Bowling Green Fault, with a vertical displacement of 100 feet at Findlay and 200 feet west of Bowling Green, has resulted in a change in the stratigraphic sequence and the hydrologic enviornment to each side of the fault (Figure 6).

Silurian System

Rocks of Silurian age are exposed in the central and southern portions of the Maumee Basin (Figure 7). The strata in ascending order are the Rochester Shale, undifferentiated Lockport Dolomite, Greenfield Dolomite, Tymochtee Dolomite, and the Raisin River Dolomite (Table I).

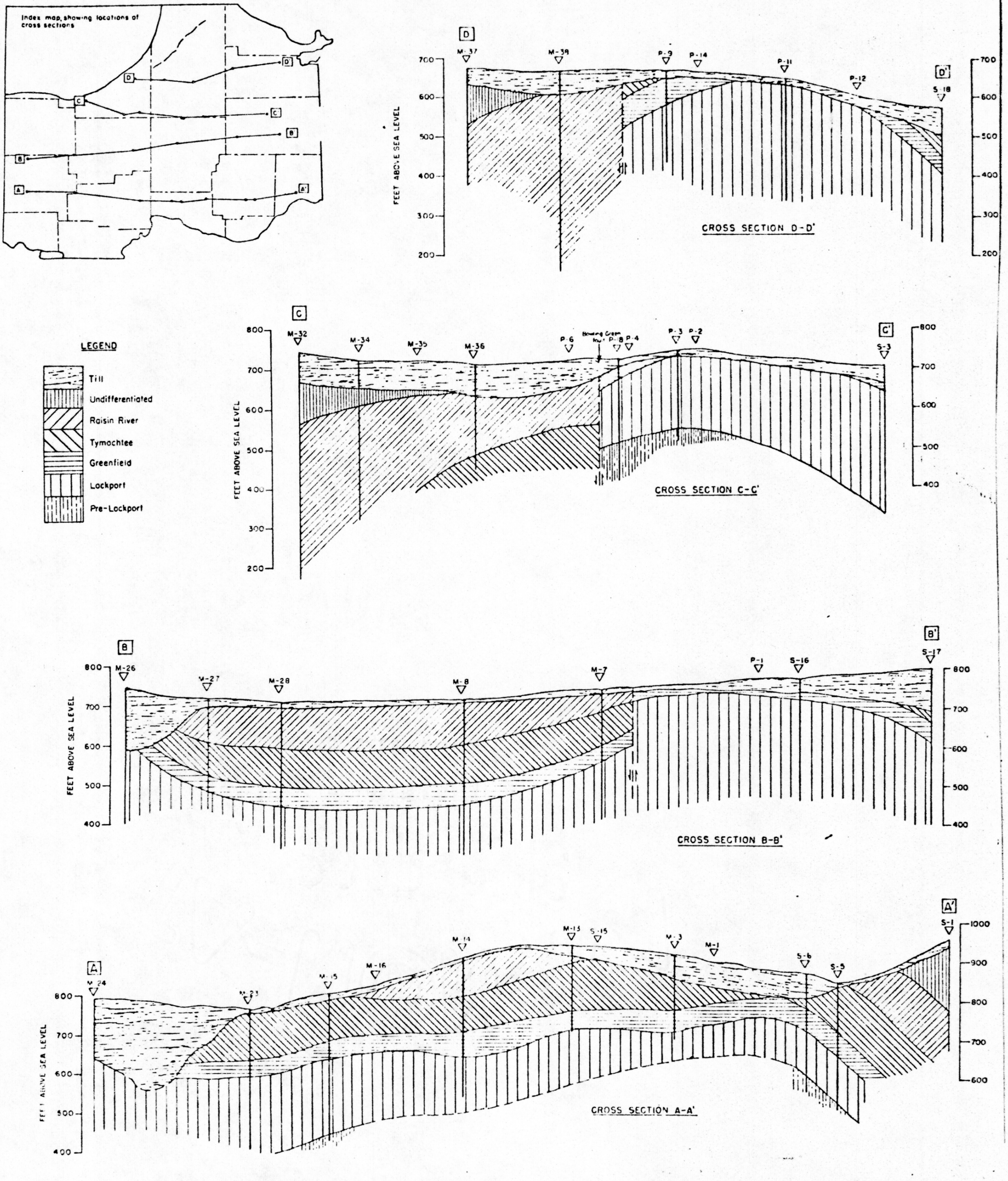

Figure 6. Geologic Cross-Sections of the Ohio Portion of the Maumee River Basin (from Ohio Water Plan Inventory, Report No. 22, 1970.)

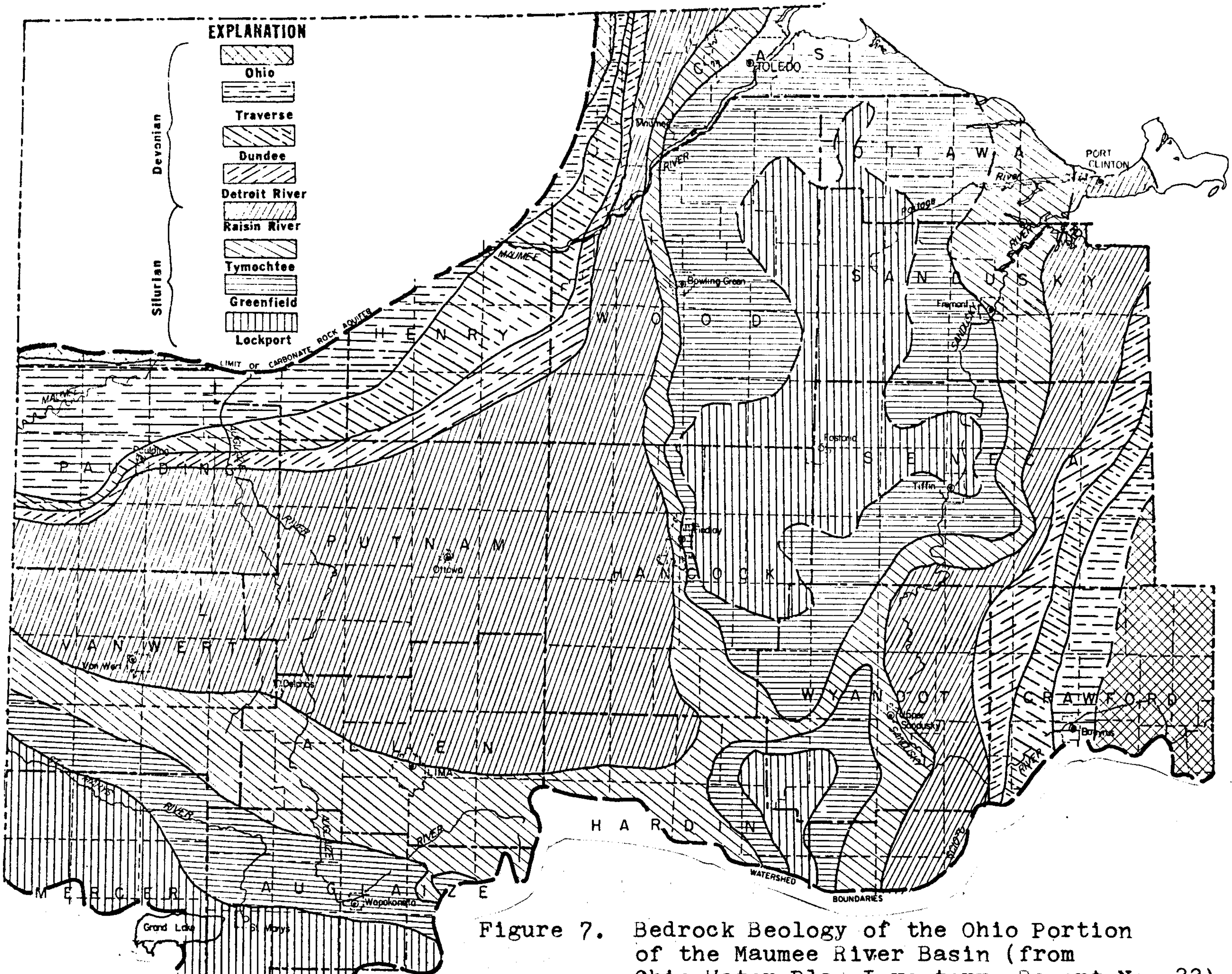

Figure 7. Bedrock Beology of the Ohio Portion of the Maumee River Basin (from Ohio Water Plan Inventory, Report No. 22)

TABLE 1

STRATIGRAPHIC COLUMN

(Division of Geological Survey)

System		Group	Formation	Average Thickness	Description	Remarks
Devonian	Upper		Ohio Shale	200	Shale, black and dark brown	
Devonian	Middle	Traverse	Ten Mile Creek Dolomite	35	Dolomite, yellowish-gray and grayish-brown, dense to medium crystalline; abundant nodular white chert	Correlative in Sandusky, Seneca, Wyandot and Crawford Counties as Prout Limestone.
Devonian	Middle	Traverse	Silica Formation	30	Limestone and shale, grayish-brown, very fossiliferous	Correlative in Sandusky, Seneca, Wyandot and Crawford Counties as Olentangy Shale.
Devonian	Middle		Dundee Limestone	50	Divided into lower and upper parts: lower of limestone and dolomite, grayish-brown, finely and medium-crystalline, sucrosic, sandy, upper part of limestone, yellowish-gray, fine- to coarse-grained, very fossiliferous; basal portion of upper Dundee lithographic limestone in much of northwest Ohio	Correlative in Sandusky, Seneca, Wyandot and Crawford Counties as Delaware Limestone.
Devonian	Middle	Detroit River	Undifferentiated	80	Dolomite, gray and brown, microcrystalline; stromatolitic in part; sandy at the base	Correlative in Sandusky, Seneca, Wyandot and Crawford Counties as Columbus Limestone.
Devonian	Middle	Detroit River	Sylvania Sandstone	25	Sandstone, white, fine- and medium-grained	
			-unconformity-			
Silurian	Upper		Raisin River Dolomite	350	Dolomite, brown, microcrystalline, medium- to thick-bedded	In VanWert County, these three formations change laterally into biohermal and biostromal dolomite that is considered an extension of the Fort Wayne carbonate bank described in adjacent areas of Indiana by Pinsak and Shaver (1964). Stratigraphic position of the Tymochtee is below the C-shale of the evaporite-bearing Salina Group in the subsurface of northwestern and northeastern Ohio
Silurian	Upper		Tymochtee Dolomite	100	Dolomite, grayish-brown, microcrystalline, thin-bedded; locally interbedded with very argillaceous dark-gray dolomite; numerous black carbonaceous partings upon weathering give shaly look to outcrops	
Silurian	Upper		Greenfield Dolomite	50	Dolomite, brown, microcrystalline, and very finely crystalline, medium-bedded, stromatolitic, sucrosic in part	
Silurian	Middle	Lockport	Undifferentiated	200	Dolomite, gray and white, finely to coarsely crystalline, fossiliferous, porous, biostromal and biohermal; in massive beds; nodular chert in lower half in many places	
Silurian	Lower		Rochester Shale	15	Shale, green; interbedded gray and greenish-gray crinoidal dolomite	

Table I. General Stratigraphic Sequence in the Maumee River Basin (from Ohio Water Plan Inventory, Report No. 22, 1970.)

The Rochester Shale is a member of the Medina Group and consists of thin to relatively thick layers of gray to green shale interbedded with thin layers of dolomite. This formation is essentially non-water bearing.

The Lockport or Niagara Dolomite is usually whitish-gray to light blue-gray porous dolomite grading to dark blue-gray at the base of the formation. This is an excellent aquifer with a locally high ground-water producing potential.

The Greenfield Dolomite is a hard, light-gray to buff dolomite of uniform thickness. It is the basal formation of the Bass Island Group of Upper Silurian age. It produces moderate to high yields of ground-water locally.

The Tymochtee Dolomite of the Bass Island Group is medium grayish-brown grading to dark-gray or black. Approximately 70% of the wells in this dolomite are productive.

The Raisin River Dolomite of the Bass Island Group is hard, dense, medium to buff, and dark-gray in color. It will produce ground-water, but only in limited quantities.

Devonian System

Rocks of Devonian age underlie the eastern portion and part of the central portion of the Maumee Basin and lie unconformably upon the Silurian System (Figure 7, Table I). In ascending order the strata consist of: the Detroit River Group, the Dundee Limestone, the Traverse Group, and the Ohio Shale (Table I).

The Detroit River Group consists of gray to tan limestone and dolomite grading to sandstones in the basal portion. It is a source of domestic supply of water and contains sulfur in some cases.

The Dundee Limestone grades from a grayish-brown limestone-dolomite to a lithographic limestone to a yellowish-gray limestone. It is considered a dependable source of water.

In the traverse Group, the Silica formation is a grayish-brown shaley-limestone which contains very small quantities of water. The Ten Mile Creek Dolomite is a yellowish-gray, dense, dolomite which is locally a fair source of water, but generally a poor source.

The Ohio Shale is a dark, dense, fissile unit. It yields small quantities of water in the upper portion where it is somewhat jointed.

Mississippian System

The Mississippian System is represented by undifferentiated dark, dense, shales in the western and northern portions of the Maumee Basin. These shales yield little or no water.

SURFICIAL GEOLOGY

The surficial geology of the basin is of two major components. The first, lacustrine deposits, covers the central portion of the basin (approximately 45% of the total area) and is composed mainly of fine sand, silt, and clay deposited on the floor of ancient Lake Maumee (Figure 2). These deposits are relatively impermeable with the exception of deep deposits of permeable sands. Low narrow beach ridges were formed during the retreat of the Wisconsin Glacier at the edges of ancient Lake Maumee (Figure 3). They are composed of sands and sandy-silts with some gravel and are capable of supplying water for domestic needs.

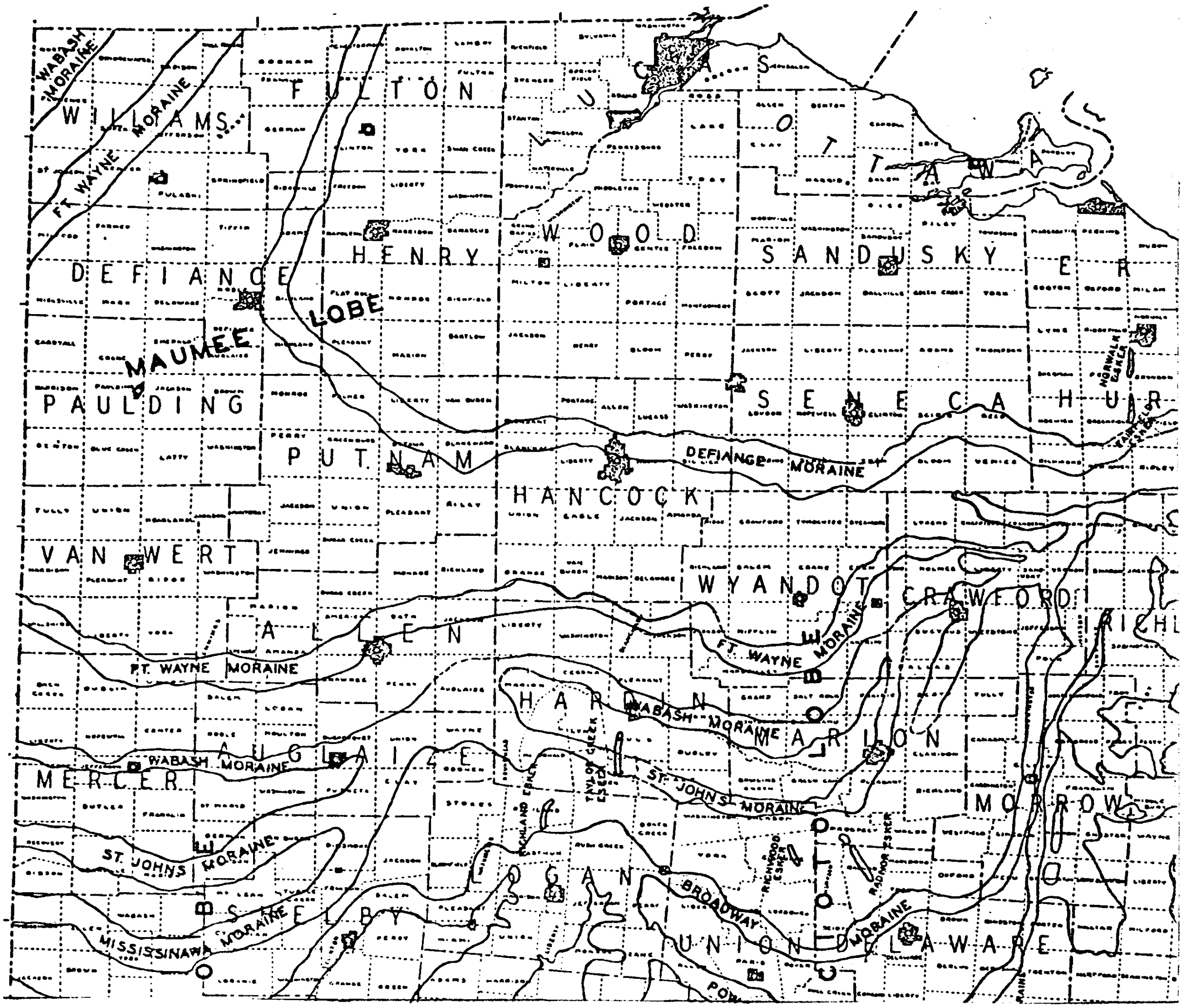

Figure 8. Morainal Deposits in the Maumee River Basin (from Stout, W., et al.,1943.)

The second component of surficial geology consists of features of the Wisconsin drift--till plains, terminal moraines, and buried valleys (Figure 2). Till plain deposits consist of a blue clay and varying amounts of rock fragments. Due to the low permeability and high mineral content, true till generally yields poor quality and low quantities of water. Between the glacial drift of the Till Plains and the bedrock surface layers of sand and gravel may exist which yield moderate amounts of ground-water. The Wabash, Defiance, and Ft. Wayne terminal moraines are located in the Maumee Basin (Figure 8). These moraines consist of unconsolidated material ranging from fine clays to gravel to boulders. In some cases they yield medium to large quantities of ground-water. During glacial and inter-glacial times, streams cut river valleys (Figure 9) which were partially filled by well-sorted outwash material in advance of the glacier and were later covered by till. These burried valleys some of which are located in Mercer and Auglaize Counties, yield excellent quantities of water in some cases.

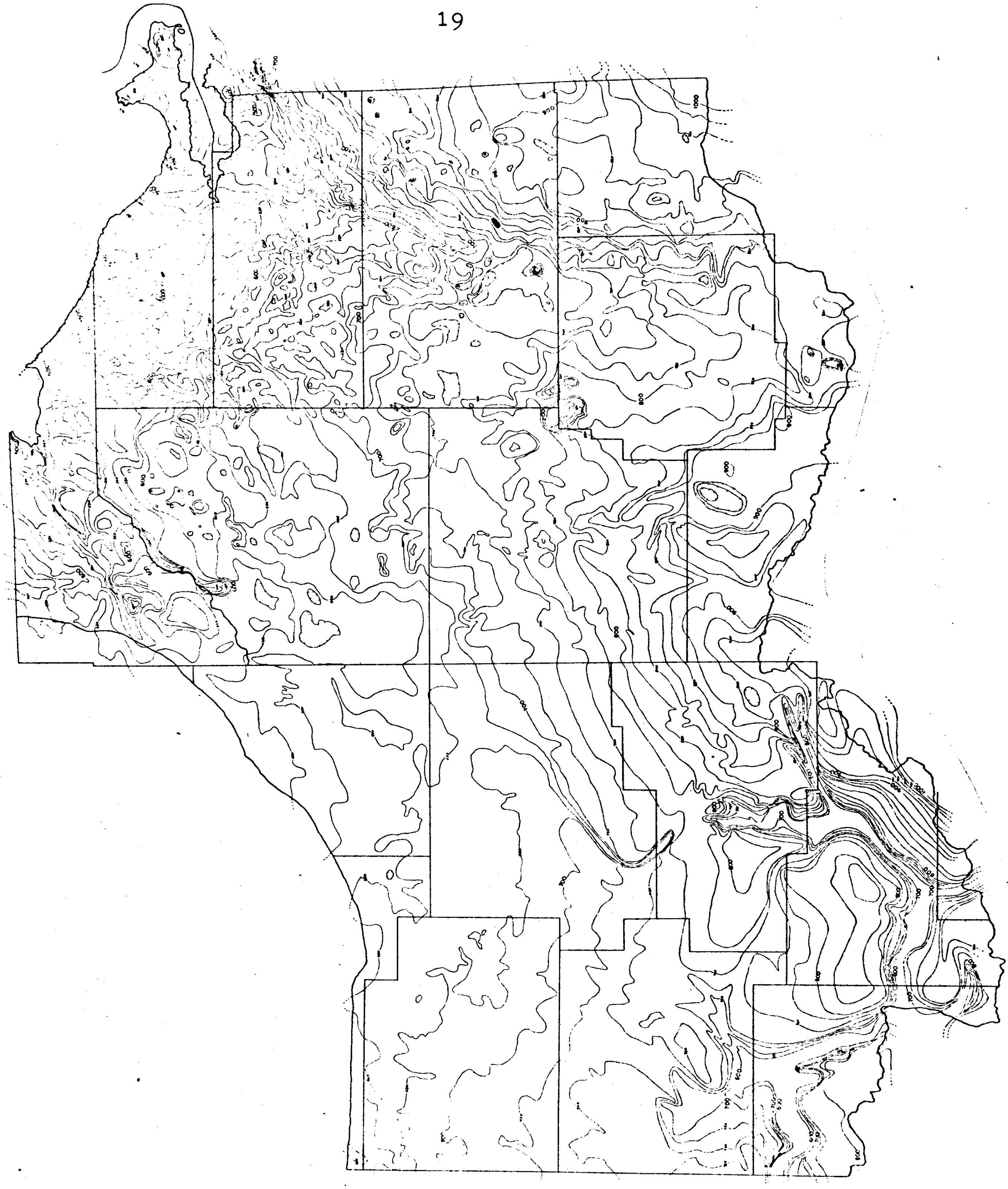

Figure 9. Bedrock Contour.Map of the Ohio Portion of the Maumee River Basin (from Ohio Water Plan Inventory, Report No. 22, 1970.)

HYROGEOLOGY OF THE BASINS

The following descriptions of the hydrogeology of the basins were taken, in part, from a series of publications by the Ohio Department of Natural Resources (Walker, A. C., 1959). The numbers preceeding the basin name refer to the appropriate stream gaging stations as published in the U. S. Geological Survey Surface Water Records for Ohio.

No. 1780--St. Joseph River Basin

The St. Joseph River Basin and its tributaries drain a total area of 1060 square miles (603 square miles in Indiana, 219 in Michingan, and 238 in Ohio). It is located in the extreme northwest corner of the Maumee Basin (Figure 1). Its southeast boundary is defined by the Ft. Wayne Moraine (Figure 8), and it therefore lies in the Till Plain region.

The bedrock of this basin consists entirely of Mississippian shales. These dark shales are considered extremely poor sources of water due to high density, low permeability, and the fact that they are deeply buried under glacial drift.

Glacial drift ranges from 170 feet to 330 feet with an average of about 250 feet for the basin. Lenticular deposits of coarse sand and gravel occurring at depths between 50 and 100 feet yield adequate domestic supplies. Supplies of over 500 gallons per minute may be obtained from large deposits of coarser material generally located at depths greater than 150 feet and often present just above the bedrock surface.

No. 1815--St. Marys River Basin

The St. Marys River Basin drains a total area of 817 square miles. It is located in the extreme southwest portion of the Maumee Basin (Figure 1). Its northeastern boundary is defined by the Ft. Wayne Moraine (Figure 8). The basin is therefore in the Till Plain area.

The bedrock of the basin is Silurian limestone and dolomite of the Bass Island and Niagara groups. Yields of 300 plus gallons per minute have been obtained at depths averaging 300 feet in these aquifers. Highest yields are obtained from wells located in bedrock in and adjacent to buried valleys, where, due to weathering numerous fractures and solution channels may occur in the bedrock.

Unconsolidated glacial deposits cover the entire basin and range in thickness from 30 feet to 400 feet in the buried valleys. The average is 65 feet in thickness. Adequate farm and domestic supplies are available throughout the basin from the drift. Thick coarse deposits of sand and gravel occur in some buried valleys and valley margin areas. These deposits yield up to 100 gallons per minute if they have access to recharge from surface streams.

Nos. 1830, 1835, and1915--Upper Maumee and Lower Auglaize River Basins

These basins are located in the west-central and central portions of the Maumee River Basin (Figure 1). They lie in the Lake Plain region of the Maumee Basin and are bound on the south and west by the Ft. Wayne Moraine (Figure 8).

The bedrock beneath most of the basin is limestone and dolomite of Silurian and Devonian age (Table 1, Figure 7). Small areas in the northern and western parts are underlain by Devonian and Mississippian shales.

The limestone bedrock is generally a good source of ground-water. The capacity of the aquifer to produce ground-water varies with locality depending on the degree of fracturing and jointing in the rock. A maximum of 200 gallons per minuet may be obtained in the limestone at depths of 300 feet or less.

Highly mineralized water may be obtained from limestone in the northern part of the basin after drilling through 10-250 feet of shale. Small yields are sometimes obtained from the upper portion of the shale where, due to weathering, it is porous enough to contain water.

Glacial drift, ranging in thickness from 20 feet in the south to 200 feet in the north covers the basin. In the north-western portion of the area, sand and gravel deposits are good sources of ground-water due to recharge from the northwest. Wells may yield as much as 1000 gallons per minute and some in Hicksville have sufficient artesian pressure to flow. Else-where in the basin, where the drift is greater than 100 feet thick, a maximum of 100 gallons per minute may be obtained from scattered sand and gravel lenses. Smaller supplies are obtained in the south as the drift cover becomes thinner.

No. 1845, No. 1850--Tiffin River Basin

The Tiffin River Basin drains 553 square miles in Ohio and 251 square miles in Michigan. It is located in the north-central portion of the Maumee River Basin (Figure 1).

The entire basin area is underlain by non-water-bearing Mississippian and Devonian shales (Table 1, Figure 7). The shale bedrock is covered with from 50 to over 250 feet of glacial drift with the greatest thickness in the northwestern part of the basin.

Extensive layers of sand and gravel are present in the drift in the western part of the area. Because of continual recharge from the northwest, these sand and gravel deposits are good sources of underground water. Although the area is largely untested, wells may yield 200 to 1000 gallons per minute for irrigation, industries, or municipalities. Most of the present wells are domestic wells for which the maximum capacities are not known. The maximum yield obtainable from sand and gravel depends to a large extent upon the methods used in construction and development of the wells.

Where surface elevations are lower than the area of recharge (along a belt from three to five miles wide and extending NNE-SSW across parts of Gorham and Franklin townships, Fulton County, Brady and Pulaski townships, Williams County, and Farmer township in Defiance County) many of the wells have sufficient artesian pressure to flow. Heavy pumping for irrigation or other large uses of water will lower water levels in the immediate vicinity. This may reduce the artesian head on nearby flowing wells and cause them to stop flowing.

The southeastern one-third of the basin is covered with an average thickness of 100 feet of drift. Sand and gravel lenses occur locally and, in places, yield up to 50 gallons per minute. Many wells, however, do not obtain adequate supplies from the drift and are drilled into the upper weathered portion of the shale where supplies of less than 10 gallons per minute are obtained.

No. 1865--Upper Auglaize River Basin

The Upper Auglaize River Basin is located in the south-central portion of the Maumee River Basin (figure 1). It runs from the Till Plains in the south to Lake Plains farther to the north (figure 2).

The Silurian limestone and dolomite bedrock is generally a good under-ground-water source. Large diameter wells which have been drilled indicate that µp to 400 gallons per minute may be obtained from the bedrock. The larger yields are obtained at depths of fromm 200 to 350 feet below the surface.. The best possibilities for developing large supplies from the bedrock are in the buried valley margin areas where the limestone may contain numerous fractures capable of containing water.

The basin is covered with an average of 60 feet of glacial drift. The drift reaches a thickness of greater than 350 feet o over the center of the main buried valley. that crosses the basin. Till in the valley and in its marginal areas contains some extensive sand and gravel deposits which, in places, will supply from 100 to 500 gallons per minute. The larger yields are obtained in portions of the buried valleys where permeable sand and gravel deposits have access to recharge by surface streams. Gravel lenses in the more shallow tributary valleys in the eastern and northwestern parts of the area are capable of supplying an average of 20 gallons per minute. Scattered sand and gravel deposits occur in the drift throughout the southern half of the basin and are often used as sources of domestic water supplies. The thickness of these deposits ranges from 5 to 80 feet. Thin drift in the northern portion of the basin is a poor source of underground water. Yields of less than 20 gallons per minute are obtained from limited sand and gravel deposits in the buried valley segment.

No. 1875--The Ottawa River Basin

The Ottawa River Basin is located in the southeastern portion of the Maumee River Basin just east of the Upper Auglaize Basin and south of the Blanchard River Basin (Figure 1).

The limestone and dolomite bedrock of Silurian and Devonian age is usually a good water source. In the vicinity of Lima, particularly in the buried valley marginal area where the rock may be fractured, yields of 500 gallons per minute are obtained at depths of around 400 feet. Elsewhere, the maximum yield from bedrock wells appears to be around 300 gallons per minute. Additional drilling may show larger yields are available in other areas.

The bedrock is covered with glacial drift, averaging 30 feet in thickness. Portions of three buried valleys are present in the basin. These valleys are remnants of old streams which had cut their courses deep into the bedrock before the area was glaciated. Later, the valleys were completely filled with drift. The deepest and most extensive buried valley, west and southwest of Lima, contains over 200 feet of fill. The fill consists largely of clay with discontinuous lenses of coarse sand and gravel deposits which range from 5 to 80 feet in thickness occur in the drift throughout the basin and are often used as sources of domestic water supplies.

No. 1890--The Blanchard River Basin

The Blanchard River Basin drains about 762 square miles and is located in the east to southeast portion of the Maumee River Basin (figure 1). Most of the basin lies in the Till Plain area (figure 2).

The bedrock beneath the basin area consists of limestone and dolomite of Silurian age (figure 7). Limestone and dolomite have very similar water-bearing properties and are both commonly called limestone. Supplies of as much as 250 gallons per minute are obtained from the limestone bedrock at depths of less than 200 feet.

The producing capacity of the limestone depends upon the number, size and water-bearing capacity of the joints and solution channels encountered. The majority of the wells in the basin were drilled for domestic supplies.

Glacial drift, which ranges from a thin veneer to 100 feet in thickness averages 25 feet in thickness in the basin. In General, little water is obtained from the glacial material although scattered sand and gravel lenses occasionally supply as much as 15 gallons per minute. These deposits are rarely greater than 10 feet thick. The best possibilities of encount - ering such deposits are in the extreme southern and northern portions of the basin.

No. 1925--Middle Portion of the Maumee River Basin

This portion of the Maumee River Basin is located i n the northeast central part of the Maumee River Basin (Figure 1). Ancient Lake Maumee entirely covered this area in the past (Figures 2 and 3).

The bedrock beneath the basin area consists of limestone and dolomite of Silurian and Devonian ages in the south, and Devonian shale in the north (Figure 7).

Small yields are sometimes available from the upper portion of the shale wher, dure to weathering, it is porous enough to contain water. Water from the shale, however, often contains varying amounts of sulfur and gas.

Limestone is genereally a good source of underground-water supplies. Wells drilled into limestone are supplied through joints and solurion openings in the rock, whose number and size vary from one locality to another within the same rock formation. Yields of as much as 200 gallons per minute may be obtained from limestone, in the basin area, at depths of 300 feet or less.

Glacial drift covering the bedrock becomes thicker from south to north, ranging from less than 50 feet near Hamler to over 180 feet in the vicinity of Wauseon. In areas where the drift is thick, it may contain coarse sand and gravel lenses of limited extent which are capable of supplying up to 100 gallons per minute to wells. Smaller supplies are obtained as the drift covering becomes thinner to the south.

TECHNIQUES FOR THE DETERMINATION OF STREAMFLOW PARAMETERS

DATA SOURCES

Streamflow data used for this study were obtained from the U.S. Geological Survey (1963, 1967, 1973). The data used represent daily mean streamflow for water years 1963, 1967, and 1973 (a water year extends from October 1 through September 30). These years were chosen to represent, as closely as possible, years of below normal (1963), near normal (1967), and above normal flow (1973).

Hydrologic Conditions

1963-Hydrologic Conditions-(U.S. Geology Survey, 1963, p. 9)--Streamflow was generally below average for the water year, with deficient flows for all months except March. Floods in the first week of March were general, with flash floods also occurring in June throughout many small basins in the central part of the State. Near the end of the water year a severe drought was developing throughout the State

1967-Hydrologic Conditions (U.S. Geology Survey, 1967, p. 9)--Streamflow in most basins in the State was about equal to the long-term average and generally the greatest since the 1961 water year. There were no extremely low flows, nor were there any damaging floods in Ohio during the 1967 water year.

1973-Hydrologic Conditions (U.S. Geology Survey, 1973, p. 11)--Streamflow for the water year was excessive, with annual mean discharges ranging from about 140 percent of the average in northeastern Ohio to about 200 percent in the northwestern parts of the State.

In central and western Ohio runoff was excessive each month of the water year except during February and May, which were near normal.

Gaging Stations

Twelve gaging stations, ten of which have no or slight artificial effects on stream discharge and two of which have moderate artificial effects on stream discharge, were chosen for this study (Figure1). Parameters discussed concerning the gagin stations with moderate artificial effects (*No. 1890 and *1915) are of questionable value. The stations are assigned numbers corresponding to those of the U. S. Geological Survey, except that the prefix 04 (indicating that they are part of the Maumee Drainage Basin) is omitted.

No. 1780--St. Joseph River near Newville, Indiana

LOCATION--Lat 41° 23'08", long 84 48'06", in SW 1/4 SW1/4 sec. 18, T.5 N., R.1 E., Defiance County, Ohio.

DRAINAGE AREA--610 mi.^{2} (1,580 km^2).

PERIOD OF RECORD--October 1946 to current year. Monthly discharge only for some periods, published in WSP 1307.

GAGE--Water-stage recorder. Datum of gage is 795.40 ft. (242.438m) above mean sea level. Prior to Oct. 22, 1947, nonrecording gage at same site and datum.

AVERAGE DISCHARGE--27 years, 498 ft^3/s (14.10 m^3/s), 11.09 in/yr (281.7 mm/yr).

REMARKS--records good for 3 water years 1963, 1967, 1973.

No. 1815 - St. Marys River at Decatur, Indiana

LOCATION.--Lat 40°50'55", long 84°56'16", in SW 1/4 SW 1/4 sec.27, T.28 N., R.14 E., Adams County.

DRAINAGE AREA.--621 mi^2 (1,608 km^2).

PERIOD OF RECORD.--October 1946 to current year. Monthly discharge only for some periods, published in WSP 1307. Gage-height records collected at site 0.5 mi (0.8km) upstream January 1932 to November 1954, and at present site thereafter are contained in reports of National Weather Service.

GAGE.--Water-stage recorder. Datum of gage is 760.44 ft (231.782 m) above mean sea level. Prior to July 27, 1948, nonrecording gage at same site and datum.

AVERAGE DISCHARGE.--27 years, 491 ft^3/s (13.91 m^3/s), 10.74 in/yr (272.8 mm/yr).

REMARKS.--Records good for water years 1963, 1967, 1973. Slight diversion from or into Wabash River basin and into Miami and Erie Canal.

No. 1830 - Maumee River at New Haven, Indiana

LOCATION.--Lat 41°05'06", long 85°01'20", in SE 1/4 NE 1/4 sec. 2, T.30 N., R. 13 E., Allen County.

DRAINAGE AREA.--1,967 mi^2 (5,095 km^2).

PERIOD OF RECORD.--December 1946 to September 1956 (high-water records only), October 1956 to current year.

GAGE.--Water-stage recorder. Datum of gage is 724.51 ft (220.831 m) above mean sea level. Prior to Sept. 7, 1956, nonrecording gage and Sept. 7, 1956 to Sept. 14, 1965, water-stage recorder at site 500 ft (152 m) downstream at same datum.

AVERAGE DISCHARGE.--17 years (1956-1973), 1,546 ft^3/s (43.78 m^3/s), 10.67 in/yr (271.0 mm/yr).

REMARKS.--Records good for water years 1963,1967, 1973. Flow slightly regulated by hydro-powerplant on the St. Joseph River 10.3 mi (16.6km) upstream from station. Flow slightly regulated by upstream reservoirs.

No. 1835 - Maumee River at Antwerp, Ohio

LOCATION.--Lat 41°11'56", long 84°44'40", in sec. 22, T. 3N., R. 1E., Pauldinge County.

DRAINAGE AREA.--2,129 mi^2 (5,514 km^2).

PERIOD OF RECORD.--September 1921 to December 1935, April 1939 to current year.

GAGE.--Water-stage recorder. Datum of gage is 694.90 ft (211.805m) above mean sea level. Prior to Sept. 13, 1925, nonrecording gage at site 400 ft (122m) upstream at same datum.

AVERAGE DISCHARGE.--48 years, 1,665 ft^3/s (47.15 m^3/s), 10.63 in/yr (270.0 mm/yr).

REMARKS.--Records good for water years 1963, 1965, 1973. Low flow is slightly regulated by powerplant at Fort Wayne, Indiana, 32 mi upstream. Flow slightly regulated by upstream reservoirs.

67 or 65

No. 1845 Bean Creek at Powers, Ohio

LOCATION.--Lat 41°40'39", long 84°13'56", in NE 1/4 sec 24, T.9 S., R.1 E., Fulton County.

DRAINAGE AREA.--206 mi^2 (534 km^2).

PERIOD OF RECORD.--October 1940 to current year.

GAGE.--Water-stage recorder. Datum of gage is 722.57 ft (220.239 m) above mean sea level. Prior to Jan. 18, 1941, nonrecording gage at same site and datum.

AVERAGE DISCHARGE.--33 years, 159 ft^3/s (4.503 m^3/s), 10.48 in/yr (266.2 mm/yr).

REMARKS.--Records good for water years 1963, 1967, 1973.

No. 1850 - Tiffin River at Stryker, Ohio

LOCATION.--Lat 41°30'17", long 84°25'49", in SW 1/4 sec. 5, T.6 N., R.4 E., Williams County.

DRAINAGE AREA.--410 mi^2 (1,060 km^2).

PERIOD OF RECORD.--September 1921 to September 1928 (published as "near Stryker"), October 1940 to current year.

GAGE.--Water-recording gage. Datum of gage is 685.1 ft (208.82 m) above mean sea level. Prior to Sept. 30, 1928, nonrecording gage at site 3.5 mi (5.6 km) downstream at different datum. Oct. 13, 1940, to Jan. 17, 1941, nonrecording gage and Jan. 18, 1941, to Sept. 30, 1953, water-stage recorder, at site 0.5 mi (0.8 km) downstream at same datum.

AVERAGE DISCHARGE.--40 years, 306 ft^3/s (8.666 m^3/s), 10.13 in/yr (257.3 mm/yr).

REMARKS.--Records fair for water years 1963, 1967, 1973.

No. 1865 - Auglaize River near Fort Jennings, Ohio

LOCATION.--Lat 40°56'55", long 84°15'58", in SE 1/4 sec. 15, T.1 S., R.5 E., Putnam County.

DRAINAGE AREA.--332 mi^2 (860 km^2).

PERIOD OF RECORD.--August 1921 to December 1935. October 1940 to current year.

GAGE.--Water-stage recorder. Datum of gage is 713.6 ft (217.51 m) above mean sea level. Prior to Oct. 6, 1930, nonrecording gage at same site and datum.

AVERAGE DISCHARGE.--47 years, 284 ft^3/s (8.043 m^3/s).

REMARK.--Records for water years 1963, 1967, 1973 good except those for January and February, which are fair. Beginning Jan. 4, 1971, water was diverted at a point 24.3 mi (39.1 km) upstream from station into Lake Bresler. Storage in Lake Bresler is available for low-flow augmentation and water supply of city of Lima, in Ottawa River basin. Net withdrawl totaled 511 mil gal (1.934 hm^3), equivalent to a mean withdrawl of 2.2 ft^3/s (0.062 m^3/s). No releases have been made for low-flow augmentation.

No. 1875 - Ottawa River at Allentown, Ohio

LOCATION.--Lat 40°45'18", long 84°11'41", in NW sec. 29, T.3 S., R.6 E., Allen County.

DRAINAGE AREA.--160 mi^2 (414 km^2).

PERIOD OF RECORD.--October 1923 to December 1935, August 1943 to current year.

GAGE.--Water-stage recorder and concrete control. Datum of gage is 789.14 ft (240.530 m) above mean sea level. Prior to Oct. 1, 1925, nonrecording gage and Oct. 1, 1925 to Dec. 30, 1935, water-stage recorder, at site 35 ft (11 m) downstream at same site and datum.

AVERAGE DISCHARGE.--42 years, 125 ft^3/s (3.540 m^3/s), 10.61 in/yr (269.5 mm/yr).

REMARKS.--Records good for water years 1963, 1967, 1973 except for the winter period, which are fair. Diurnal fluctuation caused by operation of water-supply and sewage-treatment plants of city of Lima upstream from station.

*No. 1890 - Blanchard River near Findlay, Ohio

LOCATION.--Lat 41°03'21", long 83°41'17", on east line of sec. 10, T.1 N., R.10 E., Hancock County.

DRAINAGE AREA.--346 mi^2 (896 km^2).

PERIOD OF RECORD.--October 1923 to December 1935, October 1940 to current year. Monthly discharge only fo October 1923, published in WSP 1307.

GAGE.--Water-stage recorder. Datum of gage is 754.55 ft (229.987 m) above mean sea level. Prior to July 24, 1930, nonrecording gage at same site and datum.

AVERAGE DISCHARGE.--45 years, 242 ft^3/s (6.853m^3/s), 9.50 in/yr (241.3 mm/yr).

REMARKS.--Records good for water years 1963, 1967, 1973. Water is diverted upstream from station into Findlay Reservoir. Storage in Findlay Reservoir used for water supply of city of Findlay, and is available for low-flow augmentation. All water returns to stream upstream from station. No releases have been made for low-flow augmentation.

*Auglaize River near Defiance Ohio

LOCATION.--Lat 41°14'15", long 84°23'57", in NE 1/4 sec. 9, T.3 N., R.4 E., Defiance County.

DRAINAGE AREA.--2,318 mi^2 (6,004 km^2).

PERIOD OF RECORD.--May to August 1903 (gage heights only), April 1915 to current year. Monthly discharge only for some periods, published in WSP 1307.

GAGE.--Water-stage recorder. Datum of gage is 659.70 ft (201.077 m) above mean sea level. May 20 to Aug. 8, 1903, nonrecording gage at site 1.8mi (2.9 km) downstream at different datum. Apr. 13, 1915, to Dec. 6, 1933, nonrecording gage near right bank on upstream side of dam at datum 6.0 ft (1.829 m) higher, and auxiliary tailwater staff gage near right bank on downstream side of dam at present datum.

AVERAGE DISCHARGE.--58 years, 1691 ft^3/s (47.89 m^3/s).

REMARKS.--Records good for water years 1963, 1967, 1973. Flow regulated by dam at former powerplant 125 ft (38 m) upstream from station; reservoir capacity, 9,800 acre-ft (12.1 hm^3), operation of plant discontinued Jan. 10, 1963; occaisional gate operation subsequently. Some diversion by Miami and Erie Canal from Grand Lake into Jennings Creek, tributary to Auglaize River 70 mi (113 km) upstream from station.

No. 1925 - Maumee River near Defiance, Ohio

LOCATION.--Lat 41°17'31", long 84°16'52", in NW 1/4 sec. 22. T.4 N., R.5 E., Defiance County.

DRAINAGE AREA.--5,545 mi^2 (14,362 km^2).

PERIOD OF RECORD.--October 1924 to December 1935, March 1939 to current year.

GAGE.--Water-stage recorder upstream from concrete dam. Datum of gage is 658.56 ft (200.729 m), above mean sea level. Prior to Nov. 13, 1924, nonrecording gage at same site and datum.

AVERAGE DISCHARGE.--45 years, 4,043 ft^3/sec.

REMARKS.--Records good for water years 1963, 1967, and 1973. Flow affected by occasional regulation of Auglaize River at hydroelectric plant of Toledo Edison Company, 7 mi (11 km) upstream. Operation of plant discontinued Jan. 10, 1963. Low-flow slightly regulated by powerplant at Fort Wayne, Indiana.

No. 1935 - Maumee River at Waterville, Ohio

LOCATION.--Lat 41°30'00", long 83°42'46", Lucas County.

DRAINAGE AREA.--6,330 mi^2 (16,395 km^2).

PERIOD OF RECORD.--November 1898 to December 1901, August 1921 to December 1935, March 1939 to current year.

GAGE.--Water-stage recorder. Datum of gage is 595.71 ft (181.572 m) above mean sea level. Nov. 19, 1898 to Dec. 31, 1901, Aug. 26, 1921 to July 31, 1930, nonrecording gage, Aug. 1, 1930 to Dec. 31, 1935, water-stage recorder, Mar. 14, 1939 to Mar. 12, 1940 nonrecording gage at same site and datum.

AVERAGE DISCHARGE.--48 years (1921-35, 1939-73) 4,756 ft^3/sec (134.7 m^3/s), 10.20 in/yr (259.1 mm/yr); includes flow in Miami and Erie Canal at Waterville 1922-29; canal was abandoned in 1929 and was filled in prior to March 1939.

REMARKS.--Records good for water years 1963, 1967, 1973. Low flow slightly regulated by powerplants upstream from station. Small diversion upstream from gage into Portage River basin.

RUNOFF COMPONENTS

Streamflow consists of two major components, surface runoff and ground-water runoff (Figure 10). Surface runoff is that part of precipitation which flows directly over the land surface into stream channels.

In this study the ground-water component includes interflow, bank storage (B.S. in Figure 10) and streamflow derived from the zone of saturation. Interflow is that part which moves laterally through the soil zone and is discharged into streams relatively quickly after infiltration without reaching the zone of saturation. Bank storage is the water which infiltrates the banks of a stream when the stream stage rises above the water table level and which is gradually released as the stream level falls below the zone of saturation in the river banks. The volume of bank storage depends on the maximum height of the stream stage during high runoff, duration of time the stage is maintained, and the permeability of the banks and contiguous areas. There is a time lag between maximum discharges of the various components. (See Figure 10) If more than one aquifer is present in the basin, the hydrologic properties of the aquifers determine their respective contributions to streamflow (Figure 11).

DATA PROCESSING

Electronic data processing was used in order to assemble the 13,140 daily flows into a usable form. The ground-water component was separated from total runoff making use of large scale hydrographs printed for each gaging station for each year.

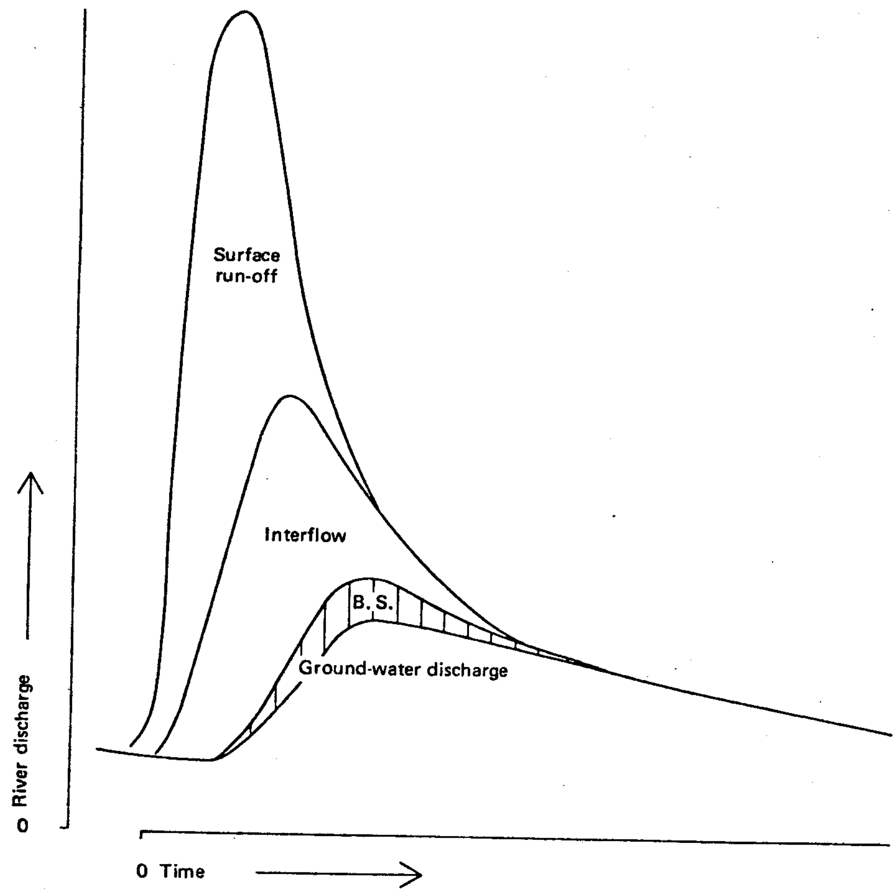

Figure 10. Components of Runoff (from Brown, R. H., et al., 1972.)

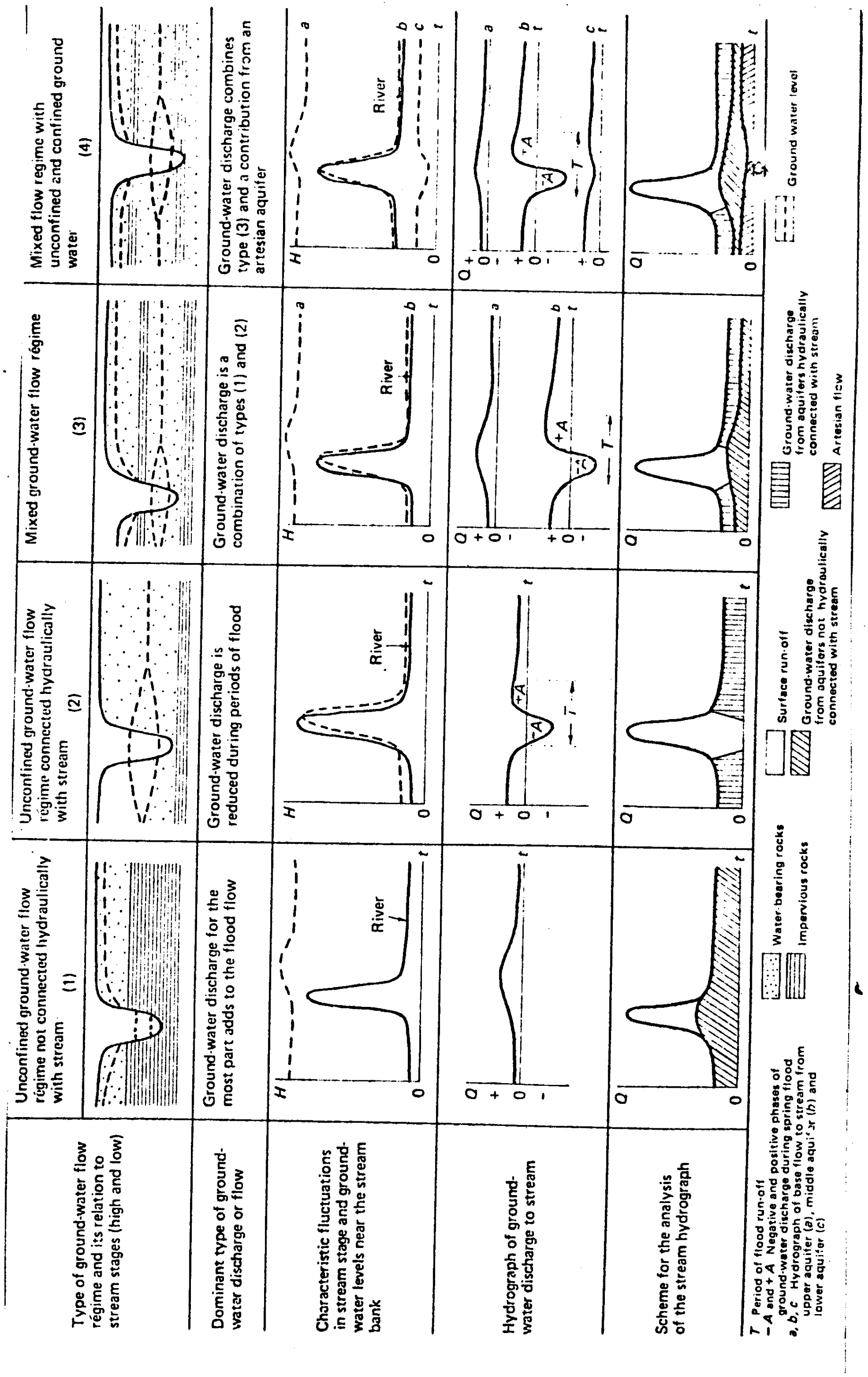

Figure 11. Analysis of Stream Hydrograph Separation (from Brown, R. H., et al., 1972.)

FORTRAN Hydrograph Program

A basic FORTRAN IV program developed by Jack Tuller and John McKeon was used in this study. This program generated from daily flow data from each gage, two streamflow hydrographs for each water year for each gaging station (a total of 72 hydrographs).

The basic program (Figure 12) as described by Tuller (1975) is as follows:

"A basic FORTRAN IV program was written that would generate from daily flow data for each gage, two streamflow hydrographs for each water year (a total of 72 hydrographs).

The basic program listing is given in figure 12. The program is divided into three main sections. The first section (up to and including statement 330) reads in daily flow data, takes the log of the flow and plots that value opposite each day of the water year. The second section (following statement 330 up to and including statement 395) calculates and prints the summary statistics. This includes maximum, minimum, mean and total discharges for the water year. The final section divides each daily flow by the basin drainage area, takes the log of this value, and then plots it opposite the appropriate day of the water year.

Typical hydrograph printouts are shown in Plate 1. The first hydrograph is printed with time, in days, aong the x-axis and discharge, in cubic feet per second, on the y-axis. The time scale is arithmetic, wheras the discharge scale is a six-cycle log scale (.1 to 100,000 cfs).

```
C THIS PROGRAM READS DAILY DISCHARGE AND PRINTS CURVE FOR EACH WATER YEAR
C ALL DISCHARGE DATA MUST BE ENTERED WITH A DECIMAL POINT
C BY JOHN B MCKEON AND JACK TULLER 1/30/75
      INTEGER PLUS,DOT
      DIMENSION STA(16),MON(365),MAP(120),DIS(365)
      REAL MDIS,LMIN,LMAX
      DATA BLANK/'    '/,PLUS/'++++'/,DOT/'....'/
      DO 20 I=1,365
   20 MON(I)=BLANK
      READ(5,40) MON(15),MON(46)       ,MON(76),MON(107),MON(138),
     *MON(166),MON(197),MON(227),MON(258),MON(288),MON(319),MON(350)
   40 FORMAT(12(A4))
      READ(5,40) MON(31),MON(61),MON(92),MON(123),MON(151),MON(182),
     *MON(212),MON(243),MON(273),MON(304),MON(335),MON(365)
      READ(5,100) STA,DRA
  100 FORMAT(16A4,1X,F7.1)
      READ(5,105)N
  105 FORMAT(I10)
      DO 50 I=1,N
   50 DIS(I)=0
      READ(5,110) DIS
  110 FORMAT(10(G8.2))
      WRITE(6,200) STA,DRA
  200 FORMAT('1',40X,16A4,2X,F8.2,2X,'SQ.MI')
      WRITE(6,210)
  210 FORMAT('0','MONTH',53X,'DISCHARGE, IN CFS')
      WRITE(6,220)
  220 FORMAT('0',4X,'.1',18X,'1',18X,'10'    ,17X,'100',15X,'1,000',14X,
     *'10,000',13X,'100,000')
      WRITE(6,230)
  230 FORMAT('0',4X,'*',6(19('+'),'*'))
      DO 300 I=1,N
      DO 250 J=1,119
  250 MAP(J)=BLANK
      MAP(120)=PLUS
      IF(MON(I).NE.DOT)GO TO 270
      IF(I.EQ.365) GO TO 270
      DO 260 KI=2,118,2
  260 MAP(KI)=DOT
  270 CONTINUE
      IF(I/2.-I/2) 271,271,274
  271 MAP(40)=DOT
      MAP(80)=DOT
  274 CONTINUE
      IF(DIS(I).EQ..0) GO TO 275
      IF(DIS(I).EQ.-1) GO TO 275
      DLOG=20*ALOG10(      DIS(I) )+20
      INDX=IFIX(2*(DLOG-IFIX(DLOG))+IFIX(DLOG))
      MAP(INDX)=PLUS
  275 WRITE(6,280) MON(I),MAP,DIS(I)
  280 FORMAT(' ',    A4,    '+',120A1,F7.1)
  300 CONTINUE
      WRITE(6,330)
      WRITE(6,220)
  330 FORMAT(' ',4X,'*',6(19('+'),'*'))
C THIS PART OF THE PROGRAM CALCULATES AND PRINTS OUT THE SUMMARY STATISTICS
      LMIN=100000.
      LMAX=.0
      TOTDIS=.0
      DO 350 I=1,N
      TOTDIS=TOTDIS+DIS(I)
      IF(DIS(I).LT.LMIN) LMIN=DIS(I)
      IF(DIS(I).GT.LMAX) LMAX=DIS(I)
  350 CONTINUE
      MDIS=TOTDIS/N
      WRITE(6,215)
  215 FORMAT('0')
      WRITE(6,360) TOTDIS
  360 FORMAT('0','TOTAL DISCHARGE FOR THE WATER YEAR',3X,F10.2,1X,
     *'CFS')
      WRITE(6,370) LMIN
  370 FORMAT('0','MINIMUM DISCHARGE',22X,F8.2,1X,'CFS')
      WRITE(6,380) MDIS
  380 FORMAT('0','MEAN DISCHARGE',25X,F8.2,1X,'CFS')
      WRITE(6,390) LMAX
```

Figure 12. Basic Program Listing (from Tuller, 1975.)

```
 390  FORMAT('0','MAXIMUM DISCHARGE',22X,F8.2,1X,'CFS')
      TDISMI=TOTDIS/DRA
      WRITE(6,215)
      WRITE(6,395) TDISMI
 395  FORMAT('0','TOTAL DISCHARGE/YR/BASIN AREA',10X,F8.2,1X,
     *'CFS/SQ.MI')
C THIS PART SETS UP AND PRINTS THE DISCHARGE/AREA OF DRAINAGE BASIN CURVE
      WRITE(6,200) STA,DRA
      WRITE(6,600)
 600  FORMAT('0','MONTH',42X,'DISCHARGE/AREA OF DRAINAGE BASIN,',
     *' CFS/SQ.MI')
      WRITE(6,610)
 610  FORMAT('0',4X,'.1',16X,'.2',16X'.4',16X,'.8',3X,'1.0',16X,
     *'2',17X,'4',17X,'8',4X,'10')
      WRITE(6,620)
 620  FORMAT('0', 4X,2('*',17('+'),'*',17('+'),'*',17('+'),'*',5('+')),
     *'*')
      DO 650 I=1,N
      DO 630 J=1,119
 630  MAP(J)=BLANK
      MAP(120)=PLUS
      IF(MON(I).NE.DOT) GO TO 635
      IF(I.EQ.365) GO TO 635
      DO 632 MI=2,118,2
 632  MAP(MI)=DOT
 635  CONTINUE
      IF(I/2.-I/2) 636,636,640
 636  MAP(36)=DOT
      MAP(60)=DOT
      MAP(96)=DOT
 640  CONTINUE
      IF(DIS(I).EQ.0) GO TO 645
      IF(DIS(I).EQ.-1) GO TO 645
      Y=DIS(I)/DRA
      IF(Y.LE..1)GO TO 645
      X=60 * ALOG10(DIS(I)/DRA)+60
      IF(X.GT.120.5) GO TO 645
      INDX=IFIX(2*(X-IFIX(X))+IFIX(X))
      MAP(INDX)=PLUS
 645  WRITE(6,280) MON(I),MAP,DIS(I)
 650  CONTINUE
      WRITE(6,621)
 621  FORMAT(' ', 4X,2('*',17('+'),'*',17('+'),'*',17('+'),'*',5('+')),
     *'*')
      WRITE(6,610)
 400  STOP
      END
```

Figure 12. Continued

The second hydrograph uses the same time scale but is printed as normalized discharge (cfs/square miles of basin area) on a two-cycle log scale (.1 to 10 cfs/sq.mi.).

HYDROGRAPH SEPARATION TECHNIQUES

The method used in the analysis of hydrographs depends on the hydraulic relationships in the basin. Three basic relationships between ground and surface waters exist (see Figure 11).

1) Aquifers having no hydraulic relationship with the stream
2) Aquifers having a continuous hydraulic relationship to the stream
3) Aquifers having intermittent hydraulic relationships with the stream

Therefore ground-water discharge may be either permanent or intermittent and may come from one or more aquifers which are unconfined, confined, or both.

Areal distribution of the ground-water discharge should be considered in the analysis of stream hydrographs. The movement of a flood wave down a river may affect the volume of ground-water discharge to differing degrees in different reaches of the river.

However, a few days after precipitation ceases, surface runoff ceases, and streamflow consists almost entirely of ground-water runoff. As stream level rises above the water table, bank storage occurs which acts as a hydraulic dam to ground-water discharge. As long as the stream level is above the water table, bank storage increases as does the water table level in general.

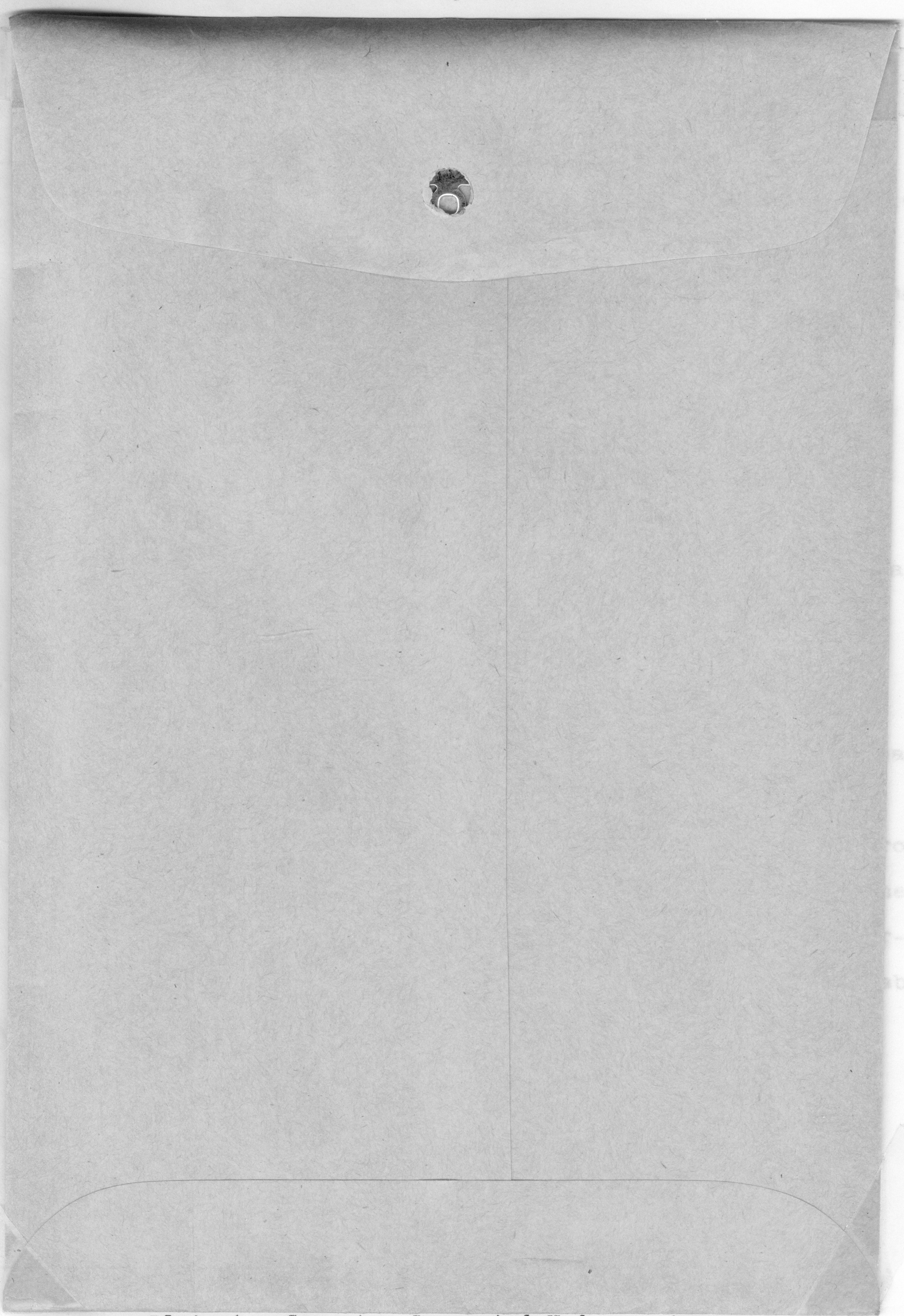

Plate 1. Computer Generated Hydrographs

This is dur to increased infiltration caused by the precipitation and due to the inability of ground-water to discharge into the stream. As the stream stage returns to normal there is a period of rapid ground-water discharge due to the steep hydraulic gradient. As the gradient decreases the amount of ground-water discharge decreases. The volume of ground-water discharge during and shortly after rainfall is difficult to calculate due to an excessive number of variables.

<u>Technique Used in This Study</u> (from Tuller, 1975)

"For the purpose of this study a straight line was drawn from the point of rise of the hydrograph at the beginning of a storm peak to a point located a distance of N days after the peak (Figure 13). The time (N) in days, being approximated by the formula $N=A^{0.2}$, where A is the area of the drainage basin, in square miles. This method is fairly simple to use and, more importantly, gives consistant results in a wide variety of streamflow situations. Once this separation is accomplished, daily values of ground-water runoff are then simply read off the hydrograph and the mean of the sum of these values is compared to the mean of the sum of the annual runoff. The results of the separations for this study are shown in Table II. This method probably gives minimum values of ground-water runoff, since the method does not allow for enough of an increase in ground-water flow during and after storms.

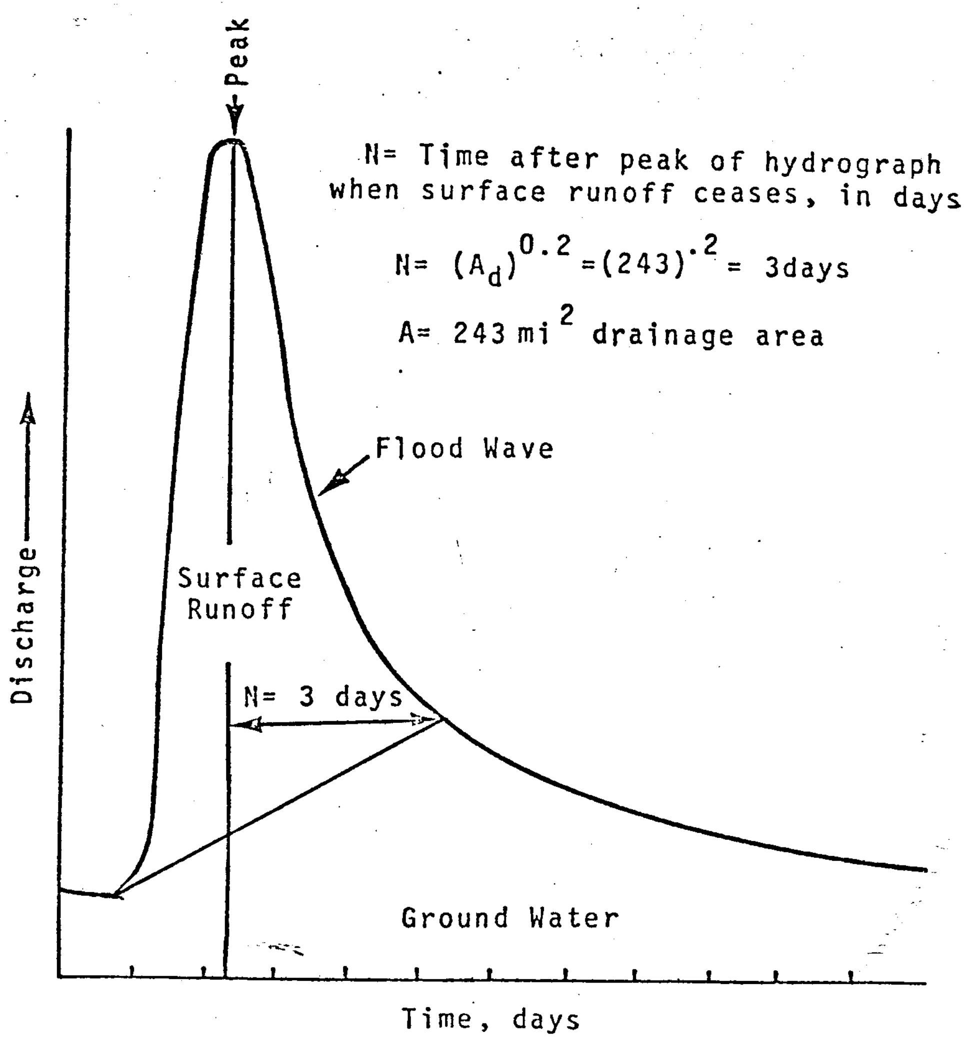

Figure 13. Hydrograph Separation Technique Used in This Study (from Tuller, 1975.)

Results of Hydrograph Separations

The actual amounts of ground-water and surface-water runoff increase in every basin from the years of below, near normal and to above normal flow. The percentage of ground-water also increases from year to year at five stations. At two stations an increase in ground-water runoff percent was observed from 1963 to 1967 and then the percentage decreased in 1973. At the remaining five stations a decrease in the percentage of ground-water runoff was observed from years of below to near to above normal runoff.

Tuller (1975, p. 44,45) found in his study of the Scioto River Basin that percentages of ground-water runoff increased in all sub-basins from years of below to near to above normal flow. He cited low antecedent soil moisture at times of low flow and high antecedent soil moisture at times of high flow as reasons for his findings. However, in the case of the Maumee River Basin other factors need to be taken into account.

The topography of the basin is, for the most part, extremely flat and almost featureless. This results in a large amount of depression storage over a great part of the basin. The amount of water capable of being held in depression storage influences the amount of infiltration. However, this amount of depression-storage water is finite. Therefore, a maximum amount of depression storage available for infiltration could be reached during periods of low to normal flow. During periods of normal to above normal flow, depending on the basin, the water not caught in depression storage would become surface runoff.

Therefore, there would be a relative increase in the percentage of surface-water runoff, and a relative decrease in the percentage of ground-water runoff.

Another possible factor to take into account is the amount of irrigation used in the three water years. In general, over 75% of the basin consists of cropland. Irrigation would naturally be more prevalent in years of below normal flow as opposed to years of above normal flow. This would yield a relative increase in ground-water runoff percentages for years of below normal flow in this particular basin.

Another factor to be considered is that in many cases, this method of hydrograph separation relies on interpretation by the individual doing the separation. This means that if the same hydrograph was analysed by a number of different people, the resulting percentages of ground-water or surface-water runoff could fall within a relatively large range.

The ranges and means of the annual ground-water runoff for the study basins have been calculated and are shown in Table III.

..ation No. & Location	Water Year	Drainage Area (sq. mi.)	Mean Annual Runoff (cfs/sq.mi.)	Mean Annual Surface-Water Runoff (cfs/sq.mi.)	Mean Annual Ground-Water Runoff (cfs/sq.mi.)	Surface-Water Runoff/Runoff (Percent)	Ground-Wate Runoff/Runo (Percent)	Basin Characteristics: Topography--Hydrogeology
No. 1780 St. Joseph River near Newville, Ind.	1963 1967 1973	609 609 610	0.330 0.749 1.232	0.159 0.222 0.430	0.171 0.527 0.802	48 30 35	52 70 65	Glaciated, till plains area, mostly cropland, glacial drift averages 250' and ranges from 170'-330'. Aquifers: sand and gravel lenses at depths of 50-100', larger supplies from coarse material located over the impermeable Mississippian shale bedrock.
No. 1815 St. Marys River At Decatur, Ind.	1963 1967 1973	621 621 621	0.378 0.873 1.329	0.179 0.408 0.606	0.199 0.465 0.723	47 47 46	53 53 54	Glaciated, till plains area, mostly cropland, limestone privcipal aquifer, most productive near buried valleys where glacial deposits may reach 400'. Glacial deposits averaged 65' and yield some domestic supplies.
No.1830 Maumee River at New Haven, Ind.	1963 1967 1973	1966 1966 1966	0.340 0.911 1.341	0.140 0.398 0.831	0.300 0.513 0.510	41 44 38	59 56 62	Glaciated, lake plains region, mostly cropland, limestone and dolomite principal aquifers; glacial drift from 20-200' with sand and gravel lenses yielding artesian flow in northwest portion due to recharge from moraine deposits to the northwest.
No. 1835 Maumee River at Antwerp, Ohio	1963 1967 1973	2128 2128 2129	0.334 0.914 1.286	0.137 0.412 0.497	0.197 0.502 0.789	41 45 39	59 55 61	Same as No. 1830 above.
N. 1845 ..n Creek at Powers, Ohio	1963 1967 1973	206 206 206	0.257 0.855 1.148	0.084 0.236 0.290	0.173 0.619 0.858	33 28 26	67 72 74	Glaciated, lake plains region, mostly cropland, non-water bearing shale bedrock, glacial drift 250' in northwestern portion with high ground-water yield sand and gravel deposits, artesian flow in some portions adjacent to Ft. Wayne Moraine, drift thins to 100' average in southeastern portion.
No. 1850 Tiffin River at Stryker, Ohio	1963 1967 1973	410 410 410	0.226 0.822 1.091	0.073 0.289 0.399	0.153 0.593 0.692	32 28 37	68 72 62	Same as No. 1845 above.

Table II. Ground-Water Surface-Water Runoff and Basin Characteristics

Station No & Location	Water Year	Drainage Area (sq.mi.)	Mean Annual Runoff (cfs/sq.mi.)	Mean Annual Surface-Water Runoff (cfs/sq.mi.)	Mean Annual Ground-Water Runoff (cfs/sq.mi.)	Surface-Water Runoff/Runoff (Percent)	Ground-Water Runoff/Runoff (Percent)	Basin Characteristics Topography- Hydrogeology
No. 1865	1963	332	0.476	0.245	0.231	52	48	Glaciated, till plains area in south and lake plains in north, mostly cropland, limestone aquifer with highest yield near buried valley crossing center of basin, glacial drift avg. 60', reaching 350' over buried valley where there are extensive sand and gravel deposits, drift thins to 5' in north.
Auglaize River	1967	332	0.976	0.549	0.427	56	44	
Fort Jennings, O.	1973	333	1.616	1.020	0.596	63	37	
No. 1875	1963	160	0.451	0.232	0.219	51	49	Glaciated till plains to lake plains, mostly cropland, limestone aquifer with highest yield near buried valley, glacial drift avg. 30', three buried valleys with drift to 200' and discontinuous lenses of sand and gravel.
Ottawa River at	1967	160	1.148	0.304	0.844	27	73	
Allentown, Ohio	1973	160	1.705	0.411	1.294	24	75	
No. 1890	1963	346	0.494	0.293	0.201	59	41	Glaciated, mostly till plains, mostly cropland, limestone aquifer, glacial drift from 0'-100', averages 25', few sand or gravel deposits.
Blanchard River	1967	346	1.022	0.644	0.378	63	37	
near Findlay, O.	1973	346	1.651	1.049	0.602	64	36	
No. 1915	1963	2318	0.328	0.210	0.118	64	36	Same as No. 1830 above.
Auglaize River	1967	2318	1.078	0.731	0.347	68	32	
Defiance, Ohio	1973	2318	1.439	0.952	0.487	66	34	
No 925	1963	5544	0.308	0.151	0.157	49	51	Glaciated, lake plains, mostly cropland, non-water bearing shales to north, limestone aquifer to south, with limitted sand and gravel lenses.
Maumee River at	1967	5544	0.924	0.495	0.429	54	46	
Defiance, Ohio	1973	5544	1.362	0.785	0.577	58	42	
No. 1935	1963	6329	0.315	0.152	0.163	48	52	Glaciated, lake plains, half croplands, half urben-suburban development, limestone aquifer, glacial drift 0'-200', average 60', shallow buried valley.
Maumee River at	1967	6329	1.007	0.576	0.431	57	43	
Waterville, Ohio	1973	6330	1.336	0.767	0.569	57	43	

Table II. Continued

RANGE

1963--0.118-0.300 cfs/sq.mi.
1967--0.347-0.844 cfs/sq.mi.
1973--0.487-1.294 cfs/sq.mi.

MEAN

1963--0.190 cfs/sq.mi.
1967--0.506 cfs/sq.mi.
1973--0.708 cfs/sq.mi.

Table III. Ranges and Means of the Annual Ground-Water Runoff for the Study Basins

FLOW-DURATION DATA AND PARAMETERS

Flow-duration data are very useful in making comparisons of the streamflow characteristics of several different streams. Flow-duration data, which show the probability of occurance of specific discharges irrespective of chronologic order, can be presented in a number of ways. Figure 14 is an example of flow-duration curves which show the percent time that a given discharge is equaled or exceeded plotted on a logarithmic scale for discharge and a probability scale for time. It is preferable to have curves prepared using daily or weekly dischages because data for longer periods of time may conceal variations in flow for the period.

Basin variables such as geology, hydrology, topography, and land use determine the shape of the curve. The shape of the curve reflects the natural ground-water storage within a basin; the more horizontal the curve, the more storage potential. For example, the Mad River with a low flat lower end to its curve (Figure 14) drains an area of glacial gravel deposits with a high ground-water storage potential. White Oak Creek drains an area of impermeable till, however, and has a steep lower end to its curve indicating a low ground-water storage potential (Figure 14).

The flow in cubic feet per second per square mile of drainage basin which is exceeded 90% of the time generally reflects the ground-water storage of a basin, although in some basins it is necessary to consider evapotranspiration. The higher the value of 90% flow, the greater is the ground water storage.

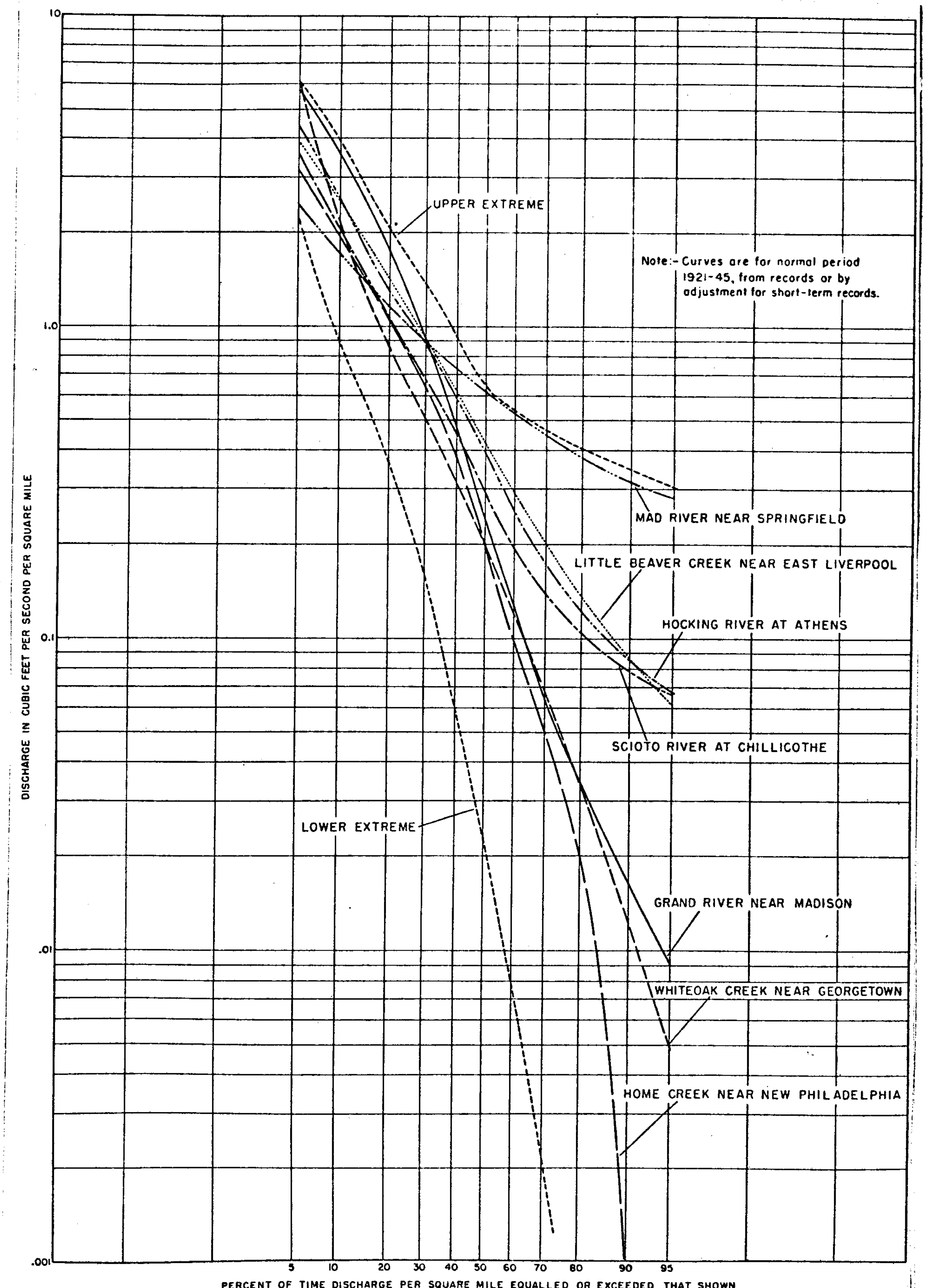

Figure 14. Flow-Duration Curves for Some Ohio Streams (from Cross and Hedges, 1959.)

The ratio $(Q_{25}/Q_{75})^{\frac{1}{2}}$ (where Q_{25} represents streamflow equalled or exceeded 25 percent of the time and Q_{75} represents streamflow equalled or exceeded 75 percent of the time), described by Walton (1970, p. 374) as equal to the slope of the duration curve, is analogous to the ratio $(D_{25}/D_{75})^{\frac{1}{2}}$ used by Pettigohn (1949) to describe the slope of grain-size frequency curves. The analogy can be made since geology (grain-size) affects streamflow to a great degree.

Technique Used for This Study

Flow-duration data were chosen representing water years of below, near, and above normal flows in an attempt to eliminate long-term variation in basin characteristics and climate. Also low-flow characteristics are better represented by periods of low precipitation and runoff.

The ratio $(Q_{25}/Q_{75})^{\frac{1}{2}}$ and $(Q_{10}/Q_{90})^{\frac{1}{2}}$ were used in this study. This allowed variations in the upper and lower ends of the curves to be observed as well as the slope of the curve. The values of flows equalled or exceeded 90, 75, 50, 25, and 10 percent of the time were also computed for each basin and water year so as to further differentiate similar basins.

DATA PROCESSING

A FORTRAN IV program developed by Jack Tuller and John McKeon in January, 1975 was used to evaluate the 13,140 daily discharges for three years at 12 gaging stations. This program generated 36 flow-duration curves and 36 flow-duration tables.

FORTRAN IV Flow-Duration Program (from Tuller, 1975)

"For this study it was desirable to construct flow-duration curves for each station for each of the three water years. These wer to be used for a gross comparison of the basins (i.e. general comparisons of the slope and shape of the curves). In addition, it was necessary to construct a flow-duration table for each station for each water year from which more exact comparisons could be made.

The basic program listing is given in Figure 15. The program, written in FORTRAN IV, is composed of two main sections.

The first section (up to statement 20) reads in the daily flow data and ranks them from lowest discharge to highest. This was actually the most difficult part of the program to write, the key to it being IF statement: IF (DIS(J).LE.DIS (J+1) GO TO 20. This statement compares each discharge with the next and rearranges them if they are not in ascending order.

The last section (statement 20 to 745) calculates the percentage of time the discharges are equalled or exceeded, divides the discharges by the basin area and plots the results in a curve and tabular form.

Examples of a flow-duration curve and data printout are shown in Plates 2 and 3, respectively. The flow-duration plot uses an arithmetic scale for the percentages (0 to 100 percent) on the x-axis and a two-cycle log scale (.1 to 10 cfs/sq.mi.) for the discharges/basin area on the y-axis. The resulting 'curve' is actually each daily flow plotted opposite its appropriate percentage of occurrence.

The flow-duration data (Plate 3) show the same results that are plotted on the curve. Each daily flow is ranked from low to high (cfs/sq.mi.) and printed beside its percentage of occurence. The data are read in rows beginning from top left (100 percent-0.030 cfs/sq.mi.) to bottom right (0.27 percent-4.793 cfs/sq.mi.). This is very useful because the percentage of occurrence for each flow can be read directly from the data printout rather than interpreting a value from the curve."

Plate 2. Computer Generated Flow-Duration Curve

Plate 3. Computer Generated Flow-Duration Data

```
C THIS PROGRAM WILL RANK ONE YEARS DAILY DISCHARGE DATA AND
C PLOT  FLOW-DURATION CURVE WITH Q AS NORMALIZED DISCHARGE, CFS/SQ. MI
C ALL DISCHARGE DATA MUST BE ENTERED WITH A DECIMAL POINT
C BY JOHN B MCKEON AND JACK TULLER 1/30/75
      INTEGER          PER(365),PLOT(101,120),DOT,PLUS,BLANK,CAPI
      DIMENSION STA(16),DISDEN(365),INDX(365),APER(365),DIS(365)
      DATA BLANK/'    '/,PLUS/'++++'/,DOT/'....'/,CAPI/'IIII'/
      READ(5,100) STA,DRA
      READ(5,210)N
  210 FORMAT(I10)
  100 FORMAT(16A4,1X,F8.2)
      READ(5,110) DIS
  110 FORMAT(10(G8.2))
      WRITE(6,200) STA,DRA
  200 FORMAT('1','FLOW-DURATION CURVE FOR',17X,16A4,2X,F8.2,2X,'SQ.MI')
      M=N-1
      DO 30 I=1,M
      L=N-I
      DO 20 J=1,L
      IF(DIS(J).LE.DIS(J+1))GO TO 20
      X=DIS(J)
      DIS(J)=DIS(J+1)
      DIS(J+1)=X
   20 CONTINUE
   30 CONTINUE
      DO 330 I=1,101
      DO 101 J=1,120
      PLOT(I,J)=BLANK
  101 CONTINUE
      PLOT(I,120)=CAPI
      IF(I/2.-I/2) 540,540,545
  540 PLOT(I,18)=DOT
      PLOT(I,36)=DOT
      PLOT(I,54)=DOT
      PLOT(I,60)=DOT
      PLOT(I,78)=DOT
      PLOT(I,96)=DOT
      PLOT(I,114)=DOT
  545 CONTINUE
      IF( I.EQ.1)GO TO 330
      IF(I.EQ.101)GO TO 330
      IF(MOD( I,10).NE.1)GO TO 330
      DO 320 J=2,118,2
      PLOT(I,J)=DOT
  320 CONTINUE
  330 CONTINUE
      DO 400 I=1,N
      APER(I)=(N-I+1.)*100/N
      PER(I)=IFIX((N-I+1.)*100/N+.5)
      DISDEN(I)=DIS(I)/DRA
      IF(DISDEN(I).LE..1)GO TO 400
      INDX(I)=IFIX(60*ALOG10(DISDEN(I))+60.5)
      IF(INDX(I).GT.120)GO TO 400
      PLOT(PER(I)+1,INDX(I))=PLUS
  400 CONTINUE
      WRITE(6,600)
  600 FORMAT('0','PERCENT'      ,54X,'FLOW, CFS/SQ.MI')
      WRITE(6,610)
  610 FORMAT('0',2X,'TIME',3X
     *                ,'.1',16X,'.2',16X,'.4',16X,'.8',3X,'1.0',16X,
     *'2',17X,'4',17X,'8',4X,'10')
      WRITE(6,620)
  620 FORMAT('0',9X,2('*',17('-'),'*',17('-'),'*',17('-'),'*',5('-')),
     *'*')
      DO 500 I=1,101
      KI=I-1
  548 IF(I.GT.1)GO TO 549
      WRITE(6,551)KI,(PLOT(I,J),J=1,120)
  551 FORMAT('+',4X,I3,2X,'I',120A1)
      GO TO 500
  549 WRITE(6,550)KI,(PLOT(I,J),J=1,120)
  550 FORMAT(' ',4X,I3,2X,'I',120A1)
  500 CONTINUE
      WRITE(6,621)
  621 FORMAT('+',9X,2('*',17('-'),'*',17('-'),'*',17('-'),'*',5('-')),
     *'*')
      WRITE(6,200)STA,DRA
      WRITE(6,710)
  710 FORMAT('0')
      DO 750 I=1,365,8
      IF(I.EQ.361) GO TO 740
      II=I+7
      WRITE(6,730)(APER(N),DISDEN(N),N=I,II)
  730 FORMAT(' ',4X,8(F6.2,1X,F6.3,3X))
  750 CONTINUE
  740 WRITE(6,745)(APER(N),DISDEN(N),N=361,365)
  745 FORMAT(' ',4X,5(F6.2,1X,F6.3,3X))
      STOP
      END
```

Figure 15. Flow-Duration Program (from Tuller, 1975.)

RESULTS OF FLOW-DURATION COMPUTATIONS

The results of the flow-duration computations are shown in Table IV. The range of the ratios $(Q_{25}/Q_{75})^{\frac{1}{2}}$ and $(Q_{10}/Q_{90})^{\frac{1}{2}}$ are shown in Table V. These results show the highest ratios for the year of normal flow (1967) and the lowest ratios for the year of below normal flow (1963). This is due to the fact that the range is greater for the year of normal flow and there is more direct runoff (hence a higher slope or $(Q_{25}/Q_{75})^{\frac{1}{2}}$ ratio). The low ratio for the year of below normal flow is a result of there being less direct runoff and more storage in the basin (either ground-water or surface-water). Similar results were obtained in calculations of $(Q_{10}/Q_{90})^{\frac{1}{2}}$ ratios.

The range of 90-percent flows is shown in Table VI. These results show the lowest 90-percent flows for the year of below normal runoff and the highest for the year of above normal flow. These are reasonable results because there is naturally more water available during years of above normal runoff. Corresponding results would be obtained in similar calculations of 70, 50, 25, and 10 percent flows.

Station No. & Location	Water Year	Drainage Area (sq. mi.)	$(Q_{25}/Q_{75})^{\frac{1}{2}}$	$(Q_{10}/Q_{90})^{\frac{1}{2}}$	90 Percent Flow (cfs/sq.mi.)	75 Percent Flow (cfs/sq.mi.)	50 Percent Flow (cfs/sq.mi.)	25 Percent Flow (cfs/sq.mi.)	10 Percent Flow (cfs/sq.mi.)	Basin Characteristics Topography--Hydrogeology
No. 1780 St. Joseph River near Newville, Ind.	1963	609	2.012	4.120	0.043	0.062	0.084	0.251	0.730	Glaciated, till plains area, mostly cropland, glacial drift averages 250' and ranges from 170'-330'. Aquifers: sand and gravel lenses at depths of 50'-100', larger supplies from coarse material located over the impermeable Mississippian shale bedrock.
	1967	609	3.795	7.147	0.041	0.063	0.296	0.893	2.094	
	1973	610	2.014	4.330	0.153	0.461	0.967	1.869	2.869	
No. 1815 St. Marys River at Decatur, Ind.	1963	621	2.378	5.878	0.022	0.029	0.052	0.164	0.760	Glaciated, till plains area, mostly cropland, limestone principal aquifer, most productive near buried valleys where glacial deposits may reach 400'. Glacial deposits average 64', and yield some domestic supplies.
	1967	621	5.199	11.550	0.023	0.032	0.155	0.865	3.068	
	1973	621	2.716	5.919	0.097	0.262	0.713	1.932	3.398	
No. 1830 Maumee River at New Haven, Ind.	1963	1966	1.970	4.423	0.049	0.059	0.077	0.229	0.959	Glaciated, lake plains region, mostly cropland, limestone and dolomite principal aquifers; glacial drift from 20'-200' with sand and gravel lenses yielding artesian flow in northwest portion due to recharge from moraine deposits to the northwest.
	1967	1966	4.025	7.441	0.047	0.071	0.291	1.150	2.602	
	1973	1966	1.990	3.917	0.196	0.468	1.004	1.845	3.007	
No. 1835 Maumee River at Antwerp, Ohio	1963	2128	1.959	4.243	0.050	0.061	0.084	0.234	0.900	Same as No. 1830 above.
	1967	2128	3.651	7.478	0.048	0.079	0.322	1.053	2.691	
	1973	2129	1.890	3.879	0.193	0.488	0.973	1.743	2.889	
No. 1845 Bean Creek at F[illegible]s, Ohio	1963	206	1.667	3.634	0.039	0.068	0.092	0.189	0.515	Glaciated, lake plains region, mostly cropland, non-water bearing shale bedrock, glacial drift 250' in northwestern portion with high ground-water yield sand and gravel deposits, artesian flow in some portions adjacent to Ft. Wayne Moraine, drift thins to 100' average in southeastern portion.
	1967	206	2.667	5.623	0.076	0.131	0.408	0.932	2.403	
	1973	206	2.227	4.804	0.124	0.330	0.823	1.636	2.862	
No. 1850 Tiffin River at Stryker, Ohio	1963	410	1.938	4.614	0.034	0.041	0.061	0.154	0.511	Same as No. 1845 above.
	1967	410	3.433	7.178	0.046	0.083	0.303	0.978	2.370	
	1973	410	2.487	6.088	0.077	0.254	0.732	1.571	2.854	

Table IV. Flow-Duration and Basin Characteristics

Station No. & Location	Water Year	Drainage Area (sq. mi.)	$(Q_{25}/Q_{75})^{\frac{1}{2}}$	$(Q_{10}/Q_{90})^{\frac{1}{2}}$	90 Percent Flow (cfs/sq.mi.)	75 Percent Flow (cfs/sq.mi.)	50 Percent Flow (cfs/sq.mi.)	25 Percent Flow (cfs/sq.mi.)	50 Percent Flow (cfs/sq.mi.)	Basin characteristics Topography--Hydrogeology
No. 1865	1963	332	2.018	4.465	0.044	0.054	0.078	0.220	0.877	Glaciated, till plains area in south and lake plains in north, mostly cropland, limestone aquifer with highest yield near buried valley crossing center of basin, glacial drift avg. 60', reaching 350' over buried valley where there are extensive sand and gravel deposits, drift thins to 5' in north.
Auglaize River	1967	333	3.372	6.588	0.054	0.084	0.262	0.955	2.344	
Fort Jennings, O.	1973	333	2.497	5.362	0.142	0.301	0.861	1.877	4.082	
No. 1875	1963	160	1.316	2.193	0.106	0.112	0.131	0.194	0.510	Glaciated till plains to lake plains, mostly cropland, limestone aquifer with highest yield near buried valley, glacial drift average 30', three buried valleys with drift to 200' and discontinuous lenses of sand and gravel.
Ottawa River at	1967	160	2.187	4.407	0.144	0.162	0.243	0.775	2.797	
Allentown, Ohio	1973	160	2.627	5.046	0.194	0.287	0.631	1.981	4.940	
No. 1890	1963	346	1.868	5.427	0.029	0.049	0.075	0.171	0.854	Glaciated, mostly till plains, mostly cropland, limestone aquifer, glacial drift from 0'-100', averages 25', few sand or gravel deopsits.
Blanchard River	1967	346	3.000	7.101	0.049	0.095	0.249	0.855	2.471	
Near Findlay, O.	1973	346	2.540	6.212	0.097	0.289	0.720	1.864	3.743	
No. 1915	1963	2318	2.910	8.353	0.009	0.017	0.053	0.144	0.628	Same as No. 1830 above.
Auglaize River	1967	2318	4.363	10.709	0.031	0.051	0.237	0.971	3.555	
Defiance, Ohio	1973	2318	2.583	7.223	0.076	0.280	0.793	1.868	3.965	
No. 1925	1963	5544	2.230	5.369	0.026	0.036	0.060	0.197	0.750	Glaciated, lake plains, mostly cropland, non-water bearing shales to north, limestone aquifer to south, with limitted sand and gravel lenses.
Maumee River at	1967	5544	4.144	8.995	0.036	0.063	0.244	1.083	2.913	
Defiance Ohio	1973	5543	2.348	5.371	0.115	0.378	0.938	2.056	3.318	
No. 1935	1963	6329	2.210	5.564	0.027	0.035	0.059	0.171	0.836	Glaciated, lake plains, half croplands, half urban-suburban development, limestone aquifer, glacial drift 0'-200', average 60', shallow buried valley.
Maumee River at	1967	6329	4.033	9.796	0.034	0.068	0.267	1.106	2.263	
Waterville, Ohio	1973	6330	2.277	5.188	0.123	0.378	0.836	1.959	3.310	

Table IV. Continued

RATIO $(Q_{25}/Q_{75})^{\frac{1}{2}}$

RANGE:	MEAN:
1963--1.316-2.910	1963--2.040
1967--2.187-5.190	1967--3.656
1973--1.890-2.716	1973--2.346

RATIO $(Q_{10}/Q_{90})^{\frac{1}{2}}$

RANGE:	MEAN:
1963--2.193-8.353	1963--4.857
1967--4.407-11.550	1967--7.835
1973--1.890-2.716	1973--5.278

TABLE V. Range and Mean of Ratios $(Q_{25}/Q_{75})^{\frac{1}{2}}$ and $(Q_{10}/Q_{90})^{\frac{1}{2}}$

Range of
90-Percent Flows

1963--.009-.106 cfs/sq.mi.
1967--.023-.144 cfs/sq.mi.
1973--.076-.196 cfs/sq.mi.

Average of
90-Percent Flows

1963-- 0.040
1967-- 0.050
1973-- 0.132

TABLE VI. Range of 90-Percent Flows
And Average of 90-Percent Flows

GROUND-WATER RECHARGE

Ground-water recharge, which is the natural rate of percolation of water to the water table, depends on variables such as the hydraulic properties of deposits, topography of the basin, type of vegetation, land use, antecedent soil moisture, depth to the water table and various climatic factors. The rate of vertical leakage of water, which determines recharge, depends on vertical permeability and thickness of deposits, areal extent of deposits, and differences in head.

Calculation of Ground-Water Recharge Using the Ground-Water Budget Concept

In general the amount of precipitation reaching the water table is equal to ground-water runoff (including underflow and bank storage), and evapotranspiration plus or minus changes in ground-water storage. Schicht and Walton (1961) used the following ground-water budget equation to incorporate the above factors:

$$P_g = R_g + ET_g + U \pm S_g$$

P_g = ground-water recharge

R_g = ground-water runoff

ET_g = ground-water evapotranspiration

U = subsurface underflow

S_g = change in ground-water storage

Annual ground-water runoff depends on antecedent soil moisture, water table stage, amount and distribution of annual precipitation and evapotranspiration. Water table stage determines the hydraulic gradient to stream level. Antecedent soil moisture determines the amount of precipitation which is retained by the upper layers of soil and thereby that which reaches the water table. Amount and distribution of rainfall determines the relative antecedent soil moisture and total water available.

Evapotranspiration, the interception and discharge into the atmosphere of water by plants, is at a maximum from April through October (the growing season). Evapotranspiration is a function of depth to the water table, with increased evapotranspiration occuring the closer the water table is to the surface of the land.

Ground-water recharge occurs only during periods when precipitation is in excess of evapotranspiration and soil moisture requirements. Therefore, in many areas ground-water recharge is the greatest in spring and early summer months of heavy rainfall when the ground is not frozen and evapotranspiration and soil moisture requirements are least.

Ground-water recharge occurs when the mean ground-water stage rises or declines less than is necessary to balance ground-water runoff and evapotranspiration. Ground-water runoff and evapotranspiration can be determined from mean ground-water stage runoff rating curves.

Change in ground-water storage (S_g) may be calculated from the following equation from Shicht and Walton 1961:

$$S_g = H(Y_g)$$

where H is the change in mean ground-water storage in feet and Y_g is the specific yield or gravity yield, which is equal to porosity minus specific retention.

Technique Used in This Study (from Tuller, 1975)

The calculation of ground-water recharge in this study is based on the amounts of ground-water runoff leaving the basins. The ground-water runoff is obtained by the hydrograph separation method outlined earlier in this chapter. This amount represents at least a minimum amount of ground-water recharge to the basin. The recharge calculated is for a period of three water years for each basin (below, near, and above normal years of flow). The water year was chosen as the period of record because it tends to minimize errors introduced by changes in ground-water storage. Ground-water levels examined for several basins (where data were available) have shown that the ground-water stage was nearly the same at the beginning and at the end of most water years.

Errors introduced by the omission of the amount of ground-water evapotranspiration are also fairly small. Schicht and Walton (1961, p. 19) estimated annual ground-water evapotranspiration to be on the order of 35,000 to 95,000 gpd/sq.mi. for three small basins in Illinois.

The amount of underflow leaving a basin varies depending on the particular situation. In studies where ground-water underflow has been calculated (Schicht and Walton, 1961, p. 20) amounts have been minimal (around 5,000 gpd/sq.mi.) and they were omitted from computations.

Results of Ground-Water Recharge Calculations

The minimum amount of annual ground-water recharge, in gpd/sq.mi., versus basin characteristics is listed in Table VII. The amounts were based on ground-water runoff data compiled through the hydrograph separations described earlier. They were calculated for each of three water years for each basin studied.

The ranges and means of annual ground-water recharge to the study basins for each of the three water years are shown in Table VIII. The ranges and means increase from the year of below normal runoff (1963) to the year of above normal runoff (1973). This increase is due to increasing precipitation resulting in increased infiltration from years of below to above normal runoff.

Basin No. & Location	Water Year	Drainage Area (sq. mi.)	Minimum Annual Ground-Water Recharge (gpd/sq. mi.)	Basin Characteristics Topography--Hydrogeology
No. 1780	1963	609	110,513	Glaciated, till plains area, mostly cropland glacial drift averages 250'; ranges from 170'-330'; aquifers: sand and gravel lenses at depths of 50-100', larger supplies from coarse material located over the impermeable Mississippian shale bedrock.
St. Joseph River	1967	609	340,585	
near Newville, Ind.	1973	610	518,310	
No. 1815	1963	621	128,608	Glaciated, till plains area, mostly cropland; limestone principal aquifer, most productive near buried valleys where glacial deposits may reach 400', glacial deposits average 65' and yield some domestic supplies.
St. Marys River	1967	621	300,516	
at Decatur, Ind.	1973	621	467,254	
No. 1830	1963	1966	129,254	Glaciated, lake plains region, mostly cropland, limestone and dolomite principal aquifers; glacial drift from 20-200' with sand and gravel lenses yielding artesian flow in northwest portion due to recharge from moraine deposits to the NW.
Maumee River	1967	1966	331,538	
at New Haven, Ind.	1973	1966	537,052	
No. 1835	1963	2128	127,316	Same as No. 1830 above.
Maumee River	1967	2128	324,429	
at Antwerp, Ohio	1973	2129	509,909	
No. 1845	1963	206	111,805	Glaciated, lake plains region, mostly cropland, non-water bearing shale bedrock, glacial drift 250' in northwestern portion with high ground-water yield sand and gravel deposits, artesian flow in some portions adjacent to Ft. Wayne Moraine, drift thins to 100' average in south-eastern portion.
Bean Creek at	1967	206	400,042	
Powers, Ohio	1973	206	554,501	
No. 1850	1963	410	98,879	Same as No. 1845 above.
Tiffin River	1967	410	383,239	
at Stryker, Ohio	1973	410	447,220	

Table VII. Ground-Water Recharge and Basin Characteristics

Basin No. & Location	Water Year	Drainage Area (sq. mi.)	Minimum Annual Ground -Water Recharge (gpd/sq. mi.)	Basin Characteristics Topography--Hydrogeology
No. 1865 Auglaize River Fort Jennings, Ohio	1963 1967 1973	332 332 332	149,289 275,958 385,178	Glaciated, till plains area in south and lake plains in north, mostly cropland, limestone aquifer with highest yield near buried valley crossin center of basin, glacial drift avg. 60' to 350' over buried valley where there are extensive sard and gravel deposits, drift thins to 5' in north.
No. 1875 Ottawa River at Allentown, Ohio	1963 1967 1973	160 160 160	141,534 545,453 836,275	Glaciated till plains to lake plains, mostly crpp land, limestone aquifer with highest yield near buried valley, glacial drift avg. 30', 3 buried valleys with drift to 200' and discontinuous lens of sand and gravel.
No. 1890 Blanchard River Findlay, Ohio	1963 1967 1973	346 346 346	129,901 244,291 389,056	Glaciated, mostly till plains, mostly cropland, limestone aquifer, glacial drift from 0-100' and avgs. 25', few sand or gravel deposits.
No. 1915 Auglaize River near Defiance, Ohio	1963 1967 1973	2318 2318 2318	76,260 224,256 314,734	Same as No. 1830 above.
No. 1925 Maumee River near Defiance, Ohio	1963 1967 1973	5544 5544 5544	101,464 277,251 372,898	Glaciated, lake plains, mostly cropland, non wate bearing shales to north, limestone aquifer to sou drift from 50-180' thins to the south, with limit sand and gravel lenses.
No. 1935 Maumee River at Waterville, Ohio	1963 1967 1973	6329 6329 6330	105,342 278,543 367,729	Glaciated, lake plains, half croplands, half urba suburban developement, limestone aquifer, glacial drift 0-200', avg. 60', shallow buried valley.

Table VII. Continued.

Range

1963-- 76,260-149,289 gpd/sq. mi.
1967--224,256-545,453 gpd/sq. mi.
1973--314,734-836,275 gpd/sq. mi.

Mean

1963-- 117,514 gpd/sq. mi.
1967-- 327,175 gpd/sq. mi.
1973-- 475,010 gpd/sq. mi.

Table VII. Range and Mean of Minimum Annual Ground-Water Recharge of the Study Basins

BASIN ANALYSES OF STREAMFLOW PARAMETERS

Variations in basin characteristics will yield different rates of ground-water recharge, ground-water runoff percentages, and flow-duration data. Basin analyses were made for each of the 12 stations in their respective basins. In some cases when basins have more than one gaging station with similar hydrology and streamflow parameters, the basins are examined as a single unit.

The average for each chosen parameter (rate of ground-water recharge, ground-water runoff percentage, the ratio $(Q_{25}/Q_{75})^{\frac{1}{2}}$ representing the index to the flow-duration curve, and percent flow that is equalled or exceeded 90% of the time) was taken for each gaging station for each water year. (Tables III, V, VI, VIII) Each station's yearly data was then compared with the average data for all of the stations.

No. 1780 St. Joseph River

This basin is characterized by impermeable shale bedrock covered by the thickest deposits of drift in the area (250' average), numerous sand and gravel lenses and extensive morainal deposits.

The St. Joseph River Basin had ground-water recharge rates and percentages of ground-water runoff that were higher than normal. (Tables VIII AND III) Its sustained, or 90% flow, ranged from near normal in 1963 to slightly below normal in 1967, to slightly above normal in 1973. (Table VI) The $(Q_{25}/Q_{75})^{\frac{1}{2}}$ ratios also varied, from slightly below normal in 1963, to slightly above normal in 1967, to slightly below normal in 1973. (Table V)

These parameters are indicative of a basin characterized by a high infiltration rate and a fairly high capability to transport ground-water to points of discharge as are also indicated by the basin characteristics. The sustained flow would probably be higher for this basin if fewer sand and gravel deposits were present as would the $(Q_{25}/Q_{75})^{\frac{1}{2}}$ ratios.

No. 1815 St. Marys River

This basin is characterized by a limestone aquifer covered by an average of 65' of glacial deposits. Three buried valleys are located in this basin where the cover of glacial drift may reach 400'. A generalized cross-section showing the relationship between glacial drift and the bedrock is shown in

Figure 16. The St. Marys River Basin had near normal ground-water recharge rates and percentages of ground-water runoff. (Tables VIII ANDIII) The sustained flows were below normal for all three water years. The $(Q_{25}/Q_{75})^{\frac{1}{2}}$ ratios were above normal for all three years.

The average rates of ground-water recharge and percentages of ground-water runoff are indicitive of the average depth of glacial deposits (65') and the normal amount of sand and gravel lenses. The low sustained flows are probably indicitive of the recharging of the three buried valleys at times of low flow. The above normal $(Q_{25}/Q_{75})^{\frac{1}{2}}$ ratios are due to low Q_{75} values caused by the recharge of buried valleys and the relatively normal Q_{25} values caused by normal rates of infiltration and runoff at higher stream stages where the affect of the buried valleys is not seen.

No. 1835 Maumee River, No. 1830 Maumee River

This basin is characterized by limestone and shale bedrock overlain by 20-200' of glacial drift with sand and gravel lenses yielding artesian flow in the northwest portion. A generalized cross-section showing the relationships between bedrock and glacial drift is shown in Figure 17. The Maumee River had above normal rates of ground-water recharge and percentage of ground-water runoff for 1963 and 1973. These Parameters were near normal for 1967. Sustained flows were near normal for 1963 and 1967, and above normal for 1973. The ratio $(Q_{25}/Q_{75})^{\frac{1}{2}}$ was below average for 1963 and 1973,

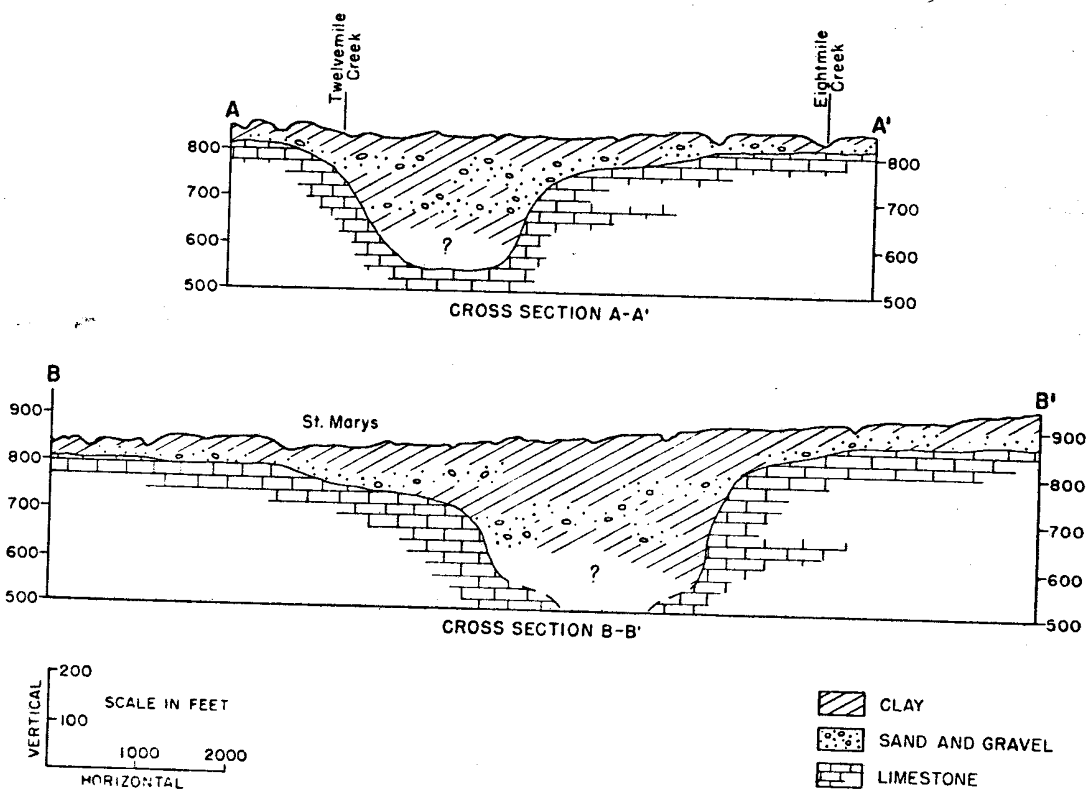

Figure 16. Generalized Cross-Sections of the St. Marys River Basin (from Ohio Water Plan Inventory, Underground Water Resources, 1959, File Index, A-1.)

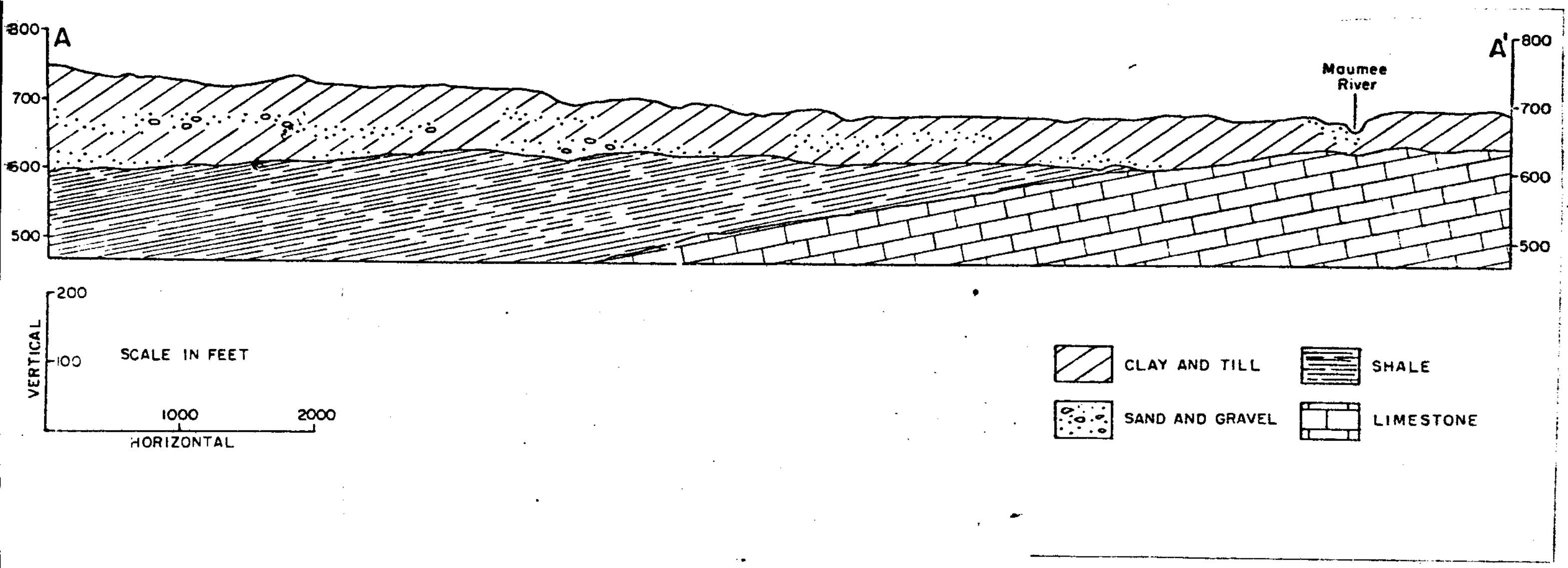

Figure 17. Generalized Cross-Section of the Upper Maumee and Lower Auglaize River Basins (from Ohio Water Plan Inventory, Underground Water Resources, File Index, A-7.)

and slightly above average in 1967.

The above to average rates of ground-water recharge and percentages of ground-water runoff are probably the results of the high recharge potential of morainal belts to the northwest connected to sand and gravel deposits in the northwest portion of the basin. Also this basin is in the flat lake plains area with an average amount of glacial cover as indicated by the average to above average sustained flows and the below to average $(Q_{25}/Q_{75})^{\frac{1}{2}}$ ratio.

No. 1845 Bean Creek

This basin is characterized by shale bedrock covered by an average of 250' of glacial drift containing large deposits of sand and gravel having artesian flow in the northwest portion of the area. Morainal deposits supply continual recharge. Figure 18 is a generalized cross-section showing the relationship between bedrock and glacial cover.

Ground-water recharge was average for 1963 and above average for 1967nand 1973. Percentages of ground-water runoff were above normal for all three years. The sustained flow was average for all three water years and the $(Q_{25}/Q75)^{\frac{1}{2}}$ ratio was below average for all three years.

These parameters are indicitive of the thick drift deposits coupled with recharge of sand and gravel deposits from the morainal belts. The values of sustained flow feflect the general characteristics of the drift and the below average $(Q_{25}/Q75)^{\frac{1}{2}}$ values reflect the low relief and high ground-water storage potential.

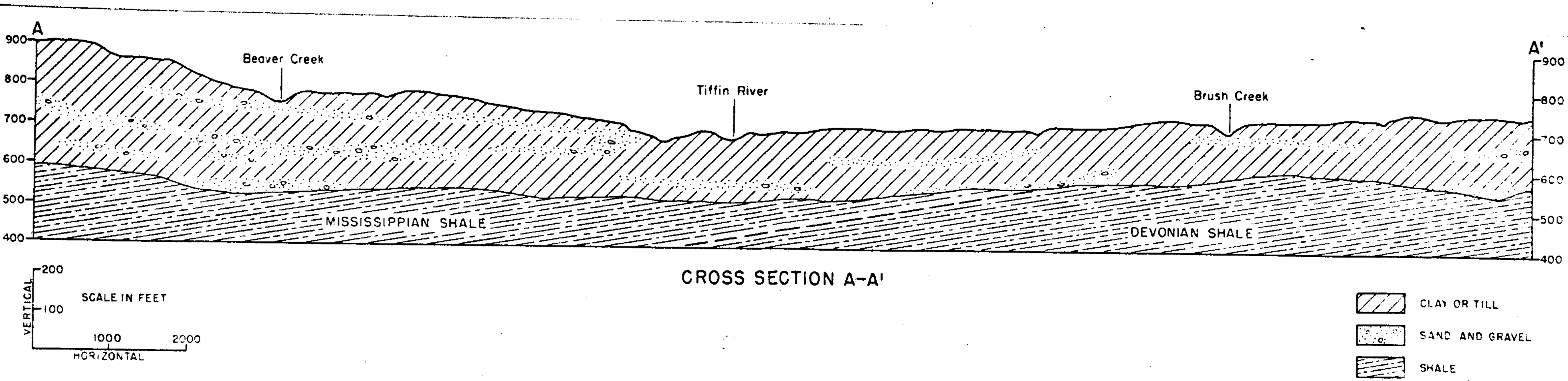

Figure 18. Generalized Cross-Section of the Tiffin River Basin (from Ohio Water Plan Inventory, Underground Water Resources, 1959, File Index A-8.)

No. 1850 Tiffin River

This lake plains basin is similar to No. 1845 except that the glacial drift is only 100' thick in this area and contains less sand and gravel. Figure 18 is a generalized cross-section depicting the relationship between the glacial drift and the shale bedrock.

The Tiffin River Basin had a ground-water recharge rate of below average for 1963 and average rates for 1967 and 1973. The percentages of ground-water runoff were above average for all three years. The sustained flow varied from average for 1963 and 1967 to below average for 1973. The $(Q_{25}/Q_{75})^{\frac{1}{2}}$ ratios were average for all three years.

These parameters are indicitive of a basin with a slightly above average ground-water storage potential. The above average percentages of greund-water runoff result from the fact that drift averages about 50' thicker here than the in the rest of the basin.

No. 1865 Auglaize River

This basin is characterized by a transition from till plains in the south to lake plains in the north. The limestone bedrock is covered with an average of 60' of drift. A buried valley crosses the center of the basin with up to 350' of glacial deposits. The drift thins to 5' in the north. Figure 19 represents a generalized cross-section of the area. This part of the Auglaize River Basin had an above average rate of ground-water recharge for 1963 and below average rates for

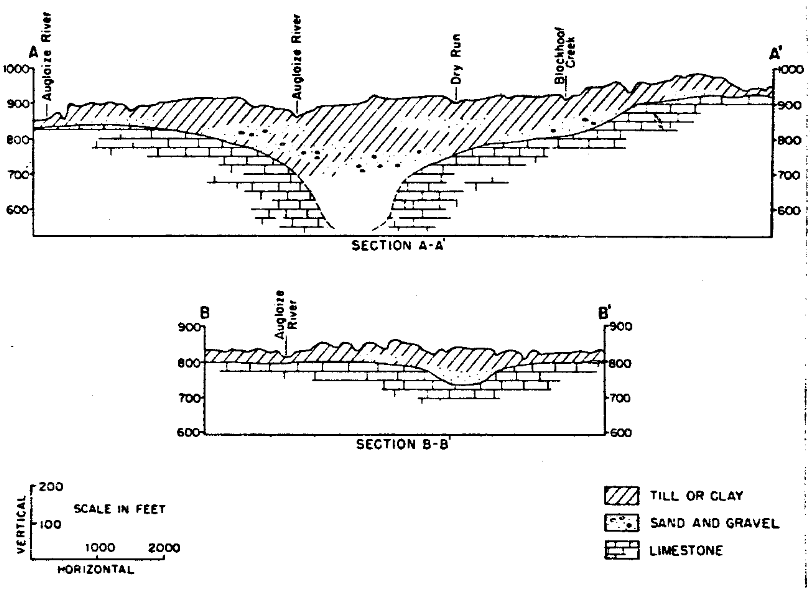

Figure 19. Generalized Cross-Section of the Upper Auglaize River Basin (from Ohio Water Plan Inventory, Underground Water Resources, File Index A-3.)

1967 and 1973. The percentages of ground-water runoff were below average for all three years. The sustained flows as well as the $(Q_{25}/Q_{75})^{\frac{1}{2}}$ ratios were average for all three years.

These parameters reflect the loss of ground-water to the buried valley, as well as the thin drift yielding little ground-water recharge. The average sustained flows and $(Q_{25}/Q_{75})^{\frac{1}{2}}$ ratios represent normal amounts of ground-water storage potential in the basin.

No. 1875 Ottawa River Basin

The Ottawa River Basin is characterized by limestone bedrock covered by an average of 30' of glacial deposits, three buried valleys, and discontinuous layers of sand and gravel from 5'-80' thick. Figure 20 represents a generalized cross-section of the area.

This river basin had above average values for the rates of ground-water recharge, percentages of ground-water runoff, and sustained flow. Values for the ratio of $(Q_{25}/Q_{75})^{\frac{1}{2}}$ were below normal for all three years.

These parameters are indicative of a vasin characterized by slow runoff with high rates of infiltration and recharge to the aquifer. Slow runoff is exemplified by low $(Q_{25}/Q_{75})^{\frac{1}{2}}$ ratios. The high storage capacity of the glacial drift is represented by above average sustained flows and groudn-water runoff.

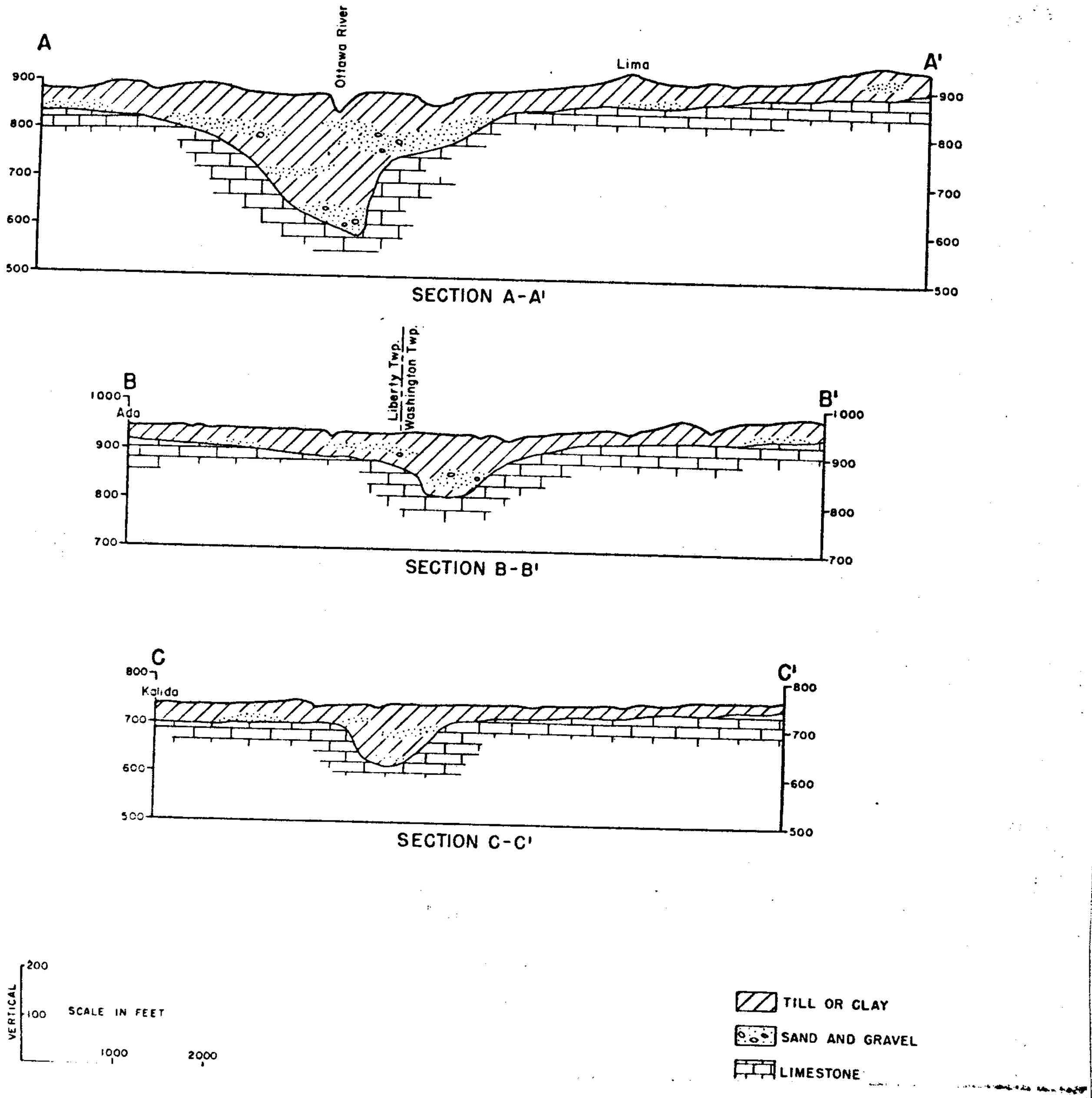

Figure 20. Generalized Cross-Section of the Ottawa River Basin (from Ohio Water Plan Inventory, Underground Water Resources, File Index A-4.)

No. 1890 Blanchard River

The Blanchard River Basin has a limestone bedrock covered by an average of 25' of glacial drift. It has very few sand and gravel deposits. Figure 21 is a generalized cross-section of the area.

This basin had an average rate of ground-water recharge for 1963 and below average rates for 1967 and 1973. The percentages of ground-water runoff were below average for all three years. The sustained flows were below average for 1963 and 1973, and were average in 1967. The values of $(Q_{25}/Q_{75})^{\frac{1}{2}}$ were below average for 1963 and 1967 and average for 1973.

These parameters indicate a basin with low infiltration rates, low ground-water storage potentials, and slow runoff. Slow runoff indicated by below normal $(Q_{25}/Q_{75})^{\frac{1}{2}}$ values is the result of the flat topography. Low infiltration rates and low ground-water storage potentials are indicated by below normal recharge rates and below normal sustained flows and runoff percentages.

No. 1915 Auglaize River Basin and Nos. 1925 & 1935 Lower Maumee River Basin

These two basins are characterized by a limestone aquifer covered with 0-200' of glacial deposits containing limeited sand and gravel deposits. Near station No. 1935 a shallow buried valley is found near the Maumee River. Figure 22 is a generalized cross-section representing the middle portion of the Maumee River Basin.

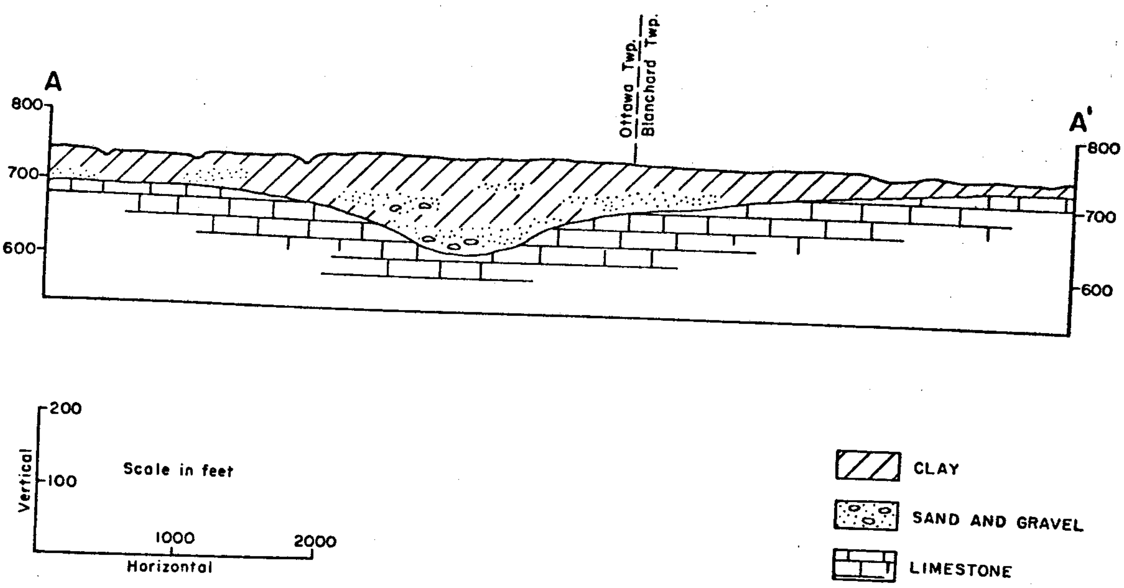

Figure 21. Generalized Cross-Section of the Blanchard River Basin (from Ohio Water Plan Inventory, Underground Water Resources, 1959, File Index A-6.)

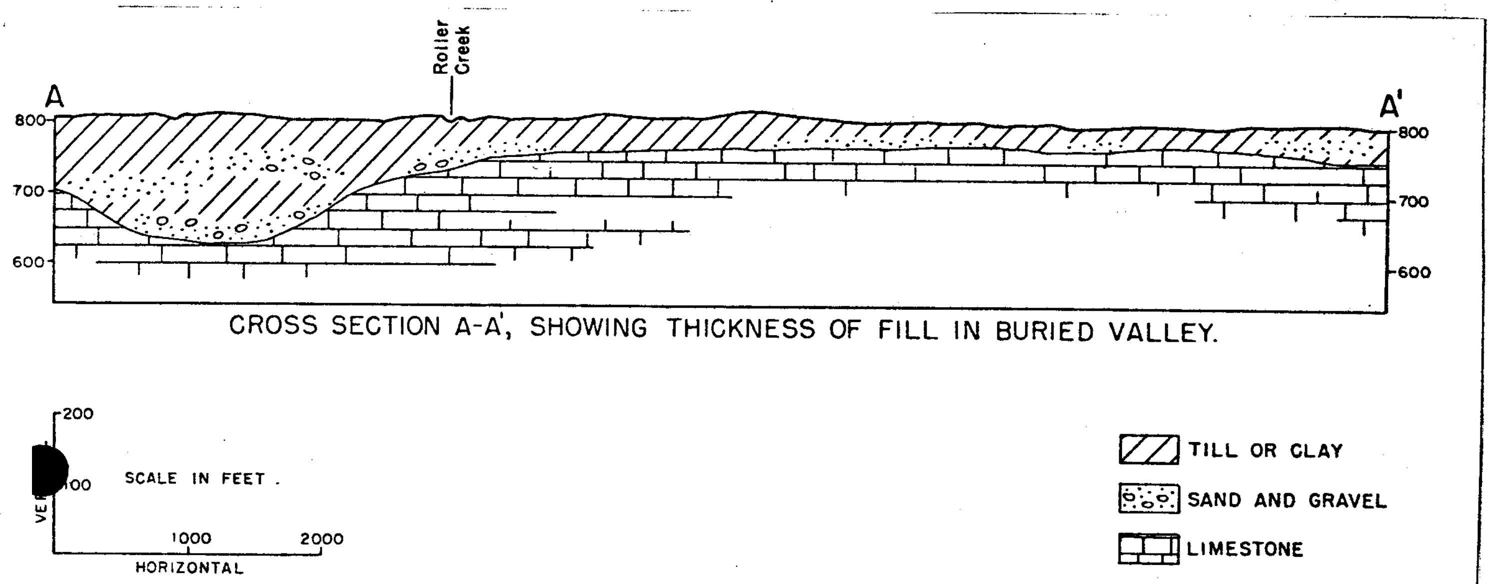

Figure 22. Generalized Cross-Section of the Middle Portion of the Maumee River Basin (from Ohio Water Plan Inventory, Underground Water Sources, 1959, File Index A-5.)

The three stations in these two basins all had below average values for rates of ground-water recharge, percentages of ground-water runoff, and sustained flows. They all had above average values of $(Q_{25}/Q_{75})^{\frac{1}{2}}$ for all three years.

These parameters are indicative of basins with low infiltration rates, slow recharge to the aquifers, and higher then average rates of runoff. This is a result of the below normal amounts of sand and gravel deposits and the effects of the buried valleys.

CONCLUSION

It is possible to place each of the study basins into one of three catagories on the basis of the streamflow parameters generated from the daily flows recorded at the gaging stations. Certain values of parameters are the result of certain basin characteristics.

Catagory I.--Till Plain Basin with Buried Valleys

Only one basin fits into this catagory (No. 1815, Figure 1). It is characterized by a limestone aquifer covered by an average of 65' of glacial drift and by three buried valleys covered by up to 400' of drift. The relatively thick drift coupled with the three buried valleys separates this basin from the others in the area.

These characteristics yield approximately average rates of ground-water recharge and ground-water runoff percentages due to the thickness of the till and normal amounts of sand and gravel deposits for the region. Below normal sustained flows are probably the results of recharge to buried valleys at times of low flows, which might be caused by increased pumpage near these valleys. Since this region is in the till plains area, runoff would be quicker than average due to increased relief of the land surface. This results in above normal $(Q_{25}/Q_{75})^{\frac{1}{2}}$ ratios.

Catagory II.--Lake Plain Basins with Relatively Shallow Glacial Drift and Limitted Sand and Gravel Deposits

Five basins fit into this catagory (Nos. 1865,1890,1915, 1925, and 1935--Figure 1). These basins are characterized by either thicker drift with few sand and gravel deposits or thin drift with relatively more sand and gravel deposits. They all have limestone bedrock and are located in the lake plains region.

All these basins are characterized by below normal rates of ground-water runoff, and sustained flows. This is a result of both the shallower drift cover and limitted sand and gravel deposits. Average to above average $(Q_{25}/Q_{75})^{\frac{1}{2}}$ ratios indicating low ground-water storage potential were recorded for the same reasons.

Catogory III.--Basins with Numerous Sand and Gravel Deposits and/or Thick Glacial Deposits

Six basins fall within this catagory (No. 1780, 1830, 1835, 1845, 1850, and 1875--Figure 1). The basins are characterized by thick drift deposits and/or numerous sand and gravel deposits. They are also characterized by good recharge sources in morainal belts or through the fact that sand and gravel lenses are located near the surface.

The above mentioned basin characteristics yield above normal rates of ground-water recharge and ground-water runoff percentages. This reflects high rates of infiltration and high storage capacities, as well as the good recharge sources in the basins. Average to above average sustained flows are also related to the high storage capacities of the basins. The $(Q_{25}/Q_{75})^{\frac{1}{2}}$ ratios were below normal in general, which reflects the slow runoff rates of the lake plains area as well as the high ground-water storage potentials.

In general, the amount of glacial cover and amount of sand and gravel deposits seem to be the major determining factors as to the values of streamflow parameters obtained. However, the effects of buried valleys, sources of recharge, and relief of the land surface should be considered as important secondary factors.

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